UTILITY SYSTEM INTEGRATION AND OPTIMIZATION MODELS FOR NUCLEAR POWER MANAGEMENT

Paul Ferris Deaton
Edward A. Mason

Work Sponsored by Commonwealth Edison Company
Chicago, Illinois

Department of Nuclear Engineering
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Cambridge, Massachusetts
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OPTIMIZATION MODELS FOR NUCLEAR POWER MANAGEMENT

by

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M.I.T. DSR PROJECT NO. 72107

Work Sponsored by

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Chicago, Illinois

Issued: June 1973
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A nuclear power management model suitable for nuclear utility systems optimization has been developed for use in multi-reactor fuel management planning over periods of up to ten years. The overall utility planning model consists of four sub-models: (1) Refueling and Maintenance Model (RAMM), (2) System Integration Model (SIM), (3) System Optimization Model (SOM), and (4) CORE Simulation and Optimization Models (CORSOM's). The SIM and SOM sub-models were developed in this study and are discussed in detail; full-scale computerized versions of each (SYSINT and SYSOPT, respectively) are evaluated as part of the methods development research.

The RAMM generates feasible, mutually exclusive nuclear refueling-fossil maintenance schedules. These are evaluated in detail by the rest of the model. Using the Booth-Baleriaux probabilistic utility system model, the SIM integrates the characteristics of the utility's plants into a representation which meets the necessary operating constraints. Scheduling of system nuclear production and detailed fossil production is done for each time period (few weeks) making up the multi-year planning horizon.

Utilizing a network programming model, the SOM optimizes the detailed production schedules of the nuclear units so as to produce the required system nuclear energy at minimum system cost. CORSOM's are utilized to optimize reload parameters (batch size and enrichment) and to generate the individual reactor fuel costs and nuclear incremental costs. These incremental costs are then used by the SOM's iterative gradient optimization technique known as the method of convex combinations.

The SYSINT model is shown to be remarkably fast, performing the Booth-Baleriaux simulation for a single time period on a system with over 45 generating units in less than 2.5 seconds on an IBM-370 model 155 computer. SYSOPT converged to optimum solutions in roughly ten iterations. Immediate reduction of iterations by roughly half is estimated by merely increasing piecewise-linearization of the network objective function. Overall model computational requirements are limited by available CORSOM's, which require 99% of the computational effort (over 3 minutes per reactor per SOM iteration).
Nuclear incremental costs ($\sim 0.8-1.6 \$/MWH) are shown to be less than fossil incremental costs ($> 2.0 \$/MWH) for the foreseeable future. Thus, nuclear power should always be operated so as to supply customer demands with a minimum use of the more expensive fossil energy. For the same reason, the lengthening of nuclear irradiation cycles (in terms of both energy and time) more than pays for itself by reducing the total cost of fossil replacement energy. Idealized nuclear production schedules yield constant nuclear incremental costs regardless of reactor unit and time. One of the key input parameters is the fossil thermal energy cost.

Thesis Supervisor: Edward A. Mason
Title: Professor of Nuclear Engineering
To the 1970-1971 President of the
Massachusetts Institute of Technology's
Technology Dames

my wife

Penelope Craig Deaton
ACKNOWLEDGMENTS

In over five years at MIT, I find myself, at this final moment, indebted to almost everyone, particularly, the Student Loan Office. Consequently, were it not for the generous support of the Atomic Energy Commission (3 years) and the John & Fannie Hertz Foundation (2-1/2 years), I would have been unable to accumulate the vast riches Penny and I now own -- Kimberly Anne and Robyn Michele. And to married students with children, the MIT Westgate Apartments are a real godsend.

With good fortune, I have come to know, during my tenure at MIT, the entire staff of the Department of Nuclear Engineering. To Professor Manson Benedict, I, like many students before me, owe the largest debt of all -- the inspiration to enter my chosen specialty. His sincerity and enthusiasm, both for the subject matter and the students themselves, bespeaks an educator in the truest sense of the word. For the sake of the students to follow, I hope his retirement is in name only. To Professor Edward A. Mason, whose painsaking editorial efforts have attempted to make this document intelligible to others besides myself, I say a profound "Thank You." For providing a receptive ear to many an idea, complaint or just plain trivia, I wish to thank fellow graduate student Joseph P. Kearney.

Many thanks also go to the Commonwealth Edison Company of Chicago for initiating the MIT research project on which this work is based. In particular, I wish to thank W. K. Kiefer and E. F. Koncel for raising many incisive questions and for providing much valuable data and many excellent ideas. Through my association with Commonwealth Edison, it was my pleasure to participate in the stimulating sessions of the Joint Systems Analysis Task Force. SYSINT, in fact, was inspired by the original TVA-ORNL model SYSSIMUL, developed by R. R. Booth.

The Out Of Kilter Network Program was graciously provided by the MIT Flight Transportation Laboratory. All computations ($5000 worth, all provided by Commonwealth Edison) were performed at the MIT Information Processing Center.

To the nine typists who gave of their time to decipher various drafts of this document: "Your accuracy was amazing!" To my new employer, Westinghouse Nuclear Energy Systems, for permitting me the run-of-the-house to complete this document (from drawing the figures to printing the document), I am most deeply indebted.

As for my long-neglected family, to my wife, words cannot express the gratitude for the many large and small things she has done to be both a mother and a father to our children as deadline after deadline slipped by unmet. Finally, to my children, who innumerable times saw Dad leave for the office before they were in bed, I answer, at long last, "Yes" to Kimmy's bedtime question, "Daddy, is your t'esis done?"
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1.1 Historical Perspective of Nuclear Power Management

The advent of commercial nuclear power created new and complex challenges to electric utility management. The utility's staff not only had to resolve difficult questions concerning safety and the environment during a nuclear plant's construction, but also ensure the economical production of energy during the plant's operating life. To aid management in this operation planning, much effort was expended incorporating nuclear power plants into existing utility system optimization models. By making reasonable and convenient assumptions (e.g., base-load operation and annual refuelings), the nuclear fuel cycle cost was determined satisfactorily and allowed a nuclear plant to be treated merely as a "fossil" plant with extremely low fuel cost.

However, as more nuclear plants are added to the grid and nuclear power makes up a larger fraction of the installed capacity, these assumptions become suspect. As a result, operating plans based on them, may be far from optimal. "Traditional methods for planning the operation of a power system cannot adequately consider nuclear fuel economics or fully recognize constraints imposed by the nature of the nuclear fuel cycle (28)."
Thus, current emphasis has shifted to developing utility nuclear power management tools which properly model nuclear plants and the complexity of the nuclear fuel cycle.

1.2 Planning Tools Needed

Utility system planners are faced with four general types of decisions:

(1) scheduling production,
(2) scheduling maintenance and refueling,
(3) purchasing new fuel and
(4) purchasing new capacity.

The above ordering of these decisions is not arbitrary. Each of these problems dominates decision-making on a longer time scale. Conversely, each characteristic time scale imposes a different set of constraints on the options available to the planner. Daily production scheduling must be performed within the context of the yearly maintenance and refueling schedules. Likewise, these scheduled outages must be coordinated with longer term fuel contracts and deliveries. Similarly, long term fuel contracts must be cognizant of future capacity additions and retirements.

The complexities of accurately and efficiently modelling the nuclear fuel cycle for each of these decisions requires four different utility system simulation models (see Figure 1.1):
Decision Variables Associated with the Hierarchy of Nuclear Utility System Planning Models

Figure 1.1

- Parameters effectively fixed for indicated model
- Future refueling dates, discharge burnups, batch sizes and enrichments for nuclear units
- Future maintenance dates for other units
- Next refueling date and discharge burnup for nuclear units
- Next maintenance date for other units
- Hourly power production level for each generating unit

Model:
- Daily (day...week)
- Annual (1 year)
- Multi-year (5 years)
- Long-range (20 years)

Planning Horizon:
(1) **Daily Model**: This model deals with the hour-by-hour dispatching of the various generating units. Only a small fraction of the energy potential in the nuclear fuel is released and the sole parameter available for optimization is the power output of each plant.

(2) **Annual Model**: This model deals with the operation of the nuclear plants between refuelings. The fuel in each reactor cannot be replaced, but the power operation of the reactor, date of the next refueling, and energy potential of the discharge fuel are decision variables for each unit. Widmer's analytical treatment of steady-state nuclear refueling (57, 59) referred to this time scale as "short-range."

(3) **Multi-year Model**: This model spans the time required for the complete nuclear fuel cycle (on the order of 5 to 10 years). In addition to the variables mentioned for the annual model, this one includes the fuel management reload variables--fuel enrichment and batch size. This time scale plays the determining role in planning for the purchase of fuel and its required processing and fabrication, as well as the financing of all these costs. In the study by Widmer (58, 59) this time scale was referred to as "mid-range."

(4) **Expansion Model**: This model covers a period of many years--on the order of the expected lifetime of generating stations--and is employed in planning for the addition and retirement of generating equipment. Within the first three models,
certain plants are assumed to exist or to have been ordered so that the type and characteristics of each unit are specified. But in the expansion model, a variety of new energy production equipment is under investigation.

Several considerations pointed to the multi-year model as deserving the initial development effort. Relative to Figure 1.1, such a model ought to have many elements useful in the development of the other three models. At the same time, the multi-year model possesses all of the complex options inherent in nuclear fuel management without the additional complexity of the plant installation decision itself. Finally, multi-year considerations vitally affect decisions regarding long-term fuel financing. Such large dollar commitments hint at large cost savings.

For these reasons, the multi-year nuclear power management model put forth in this work was developed as the first of the Commonwealth Edison-sponsored utility system optimization research projects at the Massachusetts Institute of Technology.

1.3 Introduction to Multi-year Planning

In providing installed capacity to meet the customer loads, a utility relies on up to five different types of generating equipment:

(1) Nuclear units: very large capacity units generating electricity from steam produced via the heat released by a sustained nuclear chain reaction contained within the reactor's core.
(2) Fossil steam units: typically large capacity coal, oil and/or gas-fired boilers producing steam that is expanded in turbine-generators.

(3) Fast-start peaking units: small fossil-fueled jet engine, gas turbine or diesel-driven generators.

(4) Hydro units: Typically medium capacity hydroelectric turbines associated with dams which form water reservoirs.

(5) Pumped-hydro units: similar to hydro except that its dual-purpose turbine may alternately operate as a pump, transferring water from the foot of the dam to the higher reservoir elevation. Like a storage battery, cheap off-peak energy is temporarily stored in another form (water at a height) for retrieval during the peak by reversing the process.

Regardless of the type of unit, certain key information is required by the system planner on each and every unit of the system:

(1) minimum and maximum power level,\(^1\)

(2) fuel consumption rate vs. power level,

(3) fuel cost,

(4) fuel inventory,

\(^1\) Throughout this work, all power levels are in units of net MWe delivered to the transmission system busbar. That is, plant auxiliary power requirements (~5%) have already been subtracted from gross generator output, but transmission losses have not been accounted for.
(5) transmission losses,
(6) startup-shutdown data,
(7) maintenance requirements, and
(8) reliability data.

Table 1.1 presents a general summary of these characteristics for each unit type, including capital cost estimates.

With the rates (prices) per unit electricity fixed externally by regulatory commissions and the total amount of electricity determined externally by the customers' demands, the total revenue received by the utility is also fixed (albeit, in a probabilistic sense). By minimizing the revenue required to recover the cost of supplying that electricity, the utility maximizes total profit. Therefore, the utility objective function is the minimizing of the present value of all future required revenue, i.e., the revenue requirement. (Present valuing accounts for the time value of money.) For any project, this sum represents that amount of money which, if received immediately and invested in the company, would just suffice to pay all expenses, as well as permitting a fair return to investors.\(^2\) By including investors' permitted return as another cost component, "revenue requirements" and "total cost" become synonymous.

When considering different operating strategies over a multi-year time horizon (on the order of 5 years), many of the cost components (e.g., capital investment and overhead) are essentially fixed.

The multi-year objective function may, therefore, be reduced to the operating costs directly related to supplying

\(^2\)More precisely (55),

"The revenue requirement is that sum of money, which if received as revenue by an investor-owned electric utility at the beginning of the planning horizon and invested in the enterprise, will defray all subsequent fuel cycle costs, the return allowed by regulatory agencies on that portion of the original investment remaining unexpended at any time, and defray all associated income taxes."
## Table 1.1
Characteristics of Types of Electric Generating Units

<table>
<thead>
<tr>
<th>System Use</th>
<th>Nuclear Steam (LWR)</th>
<th>Fossil Steam</th>
<th>Fast-Start Peaking</th>
<th>Hydro</th>
<th>Pumped-Hydro</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity Fact.</td>
<td>Percent</td>
<td>60-90</td>
<td>30-90</td>
<td>Up to 20</td>
<td>Up to 100</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>$/kwe</td>
<td>300-450</td>
<td>250-400</td>
<td>100-150</td>
<td>300-500</td>
</tr>
<tr>
<td>Unit Capacity</td>
<td>MW</td>
<td>500-1200</td>
<td>200-1200</td>
<td>10-50</td>
<td>10-600</td>
</tr>
<tr>
<td>Min. Power</td>
<td>% Cap.</td>
<td>10-40</td>
<td>10-50</td>
<td>75-90</td>
<td>0-10</td>
</tr>
<tr>
<td>Avg. Ht. Rate</td>
<td>MBTU/MWH</td>
<td>10.5-11</td>
<td>8.5-14</td>
<td>12-17</td>
<td>N/A</td>
</tr>
<tr>
<td>Fuel Cost</td>
<td>¢/MBTU</td>
<td>16-20</td>
<td>35-80 (Coal) 50-100 (Oil)</td>
<td>50-100</td>
<td>0</td>
</tr>
<tr>
<td>Energy Cost</td>
<td>$/MWH</td>
<td>1.7-2.2</td>
<td>3.0-8.4</td>
<td>6.5-20</td>
<td>0</td>
</tr>
<tr>
<td>Comments on Fuel Inventory</td>
<td></td>
<td>Depends on fuel cycle</td>
<td>Approx. const. at 100 days supply</td>
<td>4-8 hours (Oil)</td>
<td>Depends on season</td>
</tr>
<tr>
<td>Trans. Losses</td>
<td>Percent</td>
<td>Up to 10</td>
<td>Up to 10</td>
<td>Up to 5</td>
<td>Up to 10</td>
</tr>
<tr>
<td>SU-SD Ht. Reqt.</td>
<td>MBTU/MW Cap.</td>
<td>3-6</td>
<td>3-8</td>
<td>0-2</td>
<td>~0</td>
</tr>
<tr>
<td>Min. SD Time</td>
<td>Hours</td>
<td>&lt;2</td>
<td>2-10</td>
<td>&lt;0.3</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Maint. Reqt.</td>
<td>Week/Year</td>
<td>4-8 wk/refuel</td>
<td>3-5</td>
<td>1-4</td>
<td>1-2</td>
</tr>
<tr>
<td>Forced-Out Rate</td>
<td>Percent</td>
<td>Up to 15</td>
<td>Up to 20</td>
<td>Up to 40</td>
<td>Up to 5</td>
</tr>
<tr>
<td>Perf. Prob.</td>
<td>Percent</td>
<td>85-100</td>
<td>80-100</td>
<td>90-100</td>
<td>95-100</td>
</tr>
</tbody>
</table>
customer loads--fuel consumption within the system and net electricity purchases from neighboring utilities along with the associated taxes and carrying charges.

Adopting the notation that \( RR(X) \) is the total revenue requirement related to direct expenditure \( X \),

\[
RR(X) = \text{Present (Expenditure } X) \text{ Value} \\
\quad + \text{Present (Taxes associated with } X) \text{ Value} \\
\quad + \text{Present (Carrying charges associated with } X) \text{ Value} 
\] (1.1)

Fuel consumption expenditures can be further broken down into:

1. \( X_F \), fossil fuel related directly to on-line production,
2. \( X_N \), nuclear fuel related directly to on-line production, and
3. \( X_S \), fuel related to units' startup-shutdown heat requirements.

Expenditures for electricity purchases from other utilities, \( X_U \), represents both emergency purchases and economy purchases. (Economy purchases are not considered further in this work.)

The standard procedure in performing multi-year optimization is to subdivide the entire planning horizon into \( Z \) smaller time periods. In each time period \( p \), expenditures are estimated in undiscounted dollars. Period expenditures are then present-valued at \( x \) per year from their mean time \( \bar{t}_p \) back to time zero. As Section 1.4 will point out, the
addition of nuclear units may prevent immediate evaluation of \( X_N \). [In fact, \( RR(X_N) \) or \( RR_N \) is determined directly only after all periods have been simulated.]

The equivalent multi-year objective function \( ORR \), the operating revenue requirement, can then be expressed as

\[
ORR = RR_F + RR_N + RR_S + RR_U
\]  

or, in terms of the nonnuclear period expenditures,

\[
ORR = \sum_{p} \frac{X_F}{(1 + x)^t} \frac{1}{t_p} + RR_N \\
+ \sum_{p} \frac{X_S}{(1 + x)^t} \frac{1}{t_p} + \sum_{p} \frac{X_U}{(1 + x)^t} \frac{1}{t_p}
\]

1.4 Complexities of Nuclear Power

The cost of fossil fuel is simply the cost of coal or oil plus shipping charges. Assuming a constant coal stockpile, newly delivered coal is burned immediately. From mine to ash, fossil fuel consumption requires only a matter of some days.

Nuclear fuel, on the other hand, requires years to account for all cost components. Mining, conversion and enrichment begin a year or more before insertion in the reactor. During the three years or more of irradiation, the energy potential
is slowly extracted not only from this fuel batch, but also from two or so others in the core. Four months or more after discharge, reprocessing occurs and fissile isotope credits are received. The net result is that $\overline{T_{Cr}}$, the cost of a reactor's fuel over a time span of $C$ cycles, is a nonlinear, nonseparable function of the energy produced in each cycle, $E_{rc}$.

$$\overline{T_{Cr}} = \overline{T_{Cr}} (E_{r1}, E_{r2}, \ldots, E_{rc})$$ (1.4)

Summing each reactor's total fuel cost (i.e., revenue requirement) yields the system nuclear revenue requirement, $R_{RN}$,

$$R_{RN} = \overline{T_{C}} = \sum_{r=1}^{R} \overline{T_{Cr}}$$ (1.5)

Qualitatively, the nonlinearity,

$$\overline{T_{Cr}} \neq \alpha_{r0} + \alpha_{r1} E_{r1} + \alpha_{r2} E_{r2} + \ldots + \alpha_{rc} E_{rc}$$ (1.6)

results from the fact that, given the refueling batch fractions, cycle energy is approximately linear in reload enrichment,
but the cost of this enrichment (i.e., separative work requirement) is nonlinear.

Preventing a more general uncoupling of the cycle energies,

\[
\overline{TC_r} \neq C_{r0} + C_{r1}(E_{r1}) + C_{r2}(E_{r2}) + \ldots + C_{rc}E_{rc} (1.7)
\]

is the multi-irradiation (multi-zone) nature of today's LWR refueling schemes. The specification of reload enrichments requires not only reactivity allowance for the next cycle, but succeeding ones as well.

In summary, to calculate nuclear fuel costs, the cycle energies to the horizon of interest must be known.

In the early years of nuclear power, this stringent requirement did not pose a problem for conventional production scheduling models. With only one nuclear plant on a system (see Figure 1.2), base-load operation was possible. That is, nuclear units were operated at full capacity whenever they were available. (In addition, annual refueling meshed nicely with fossil maintenance plans and appeared to be reasonably economical.) For the base-load case (i.e., availability-based capacity factor for unit \( r, L'_r = 1 \)), cycle energy \( E_{rc} \) could be immediately determined since

\[
E_{rc} = p_r T_{rc} K_r L'_r \tag{1.8}
\]
Nuclear Capacity Greater than Minimum Load

Figure 1.2

MINIMUM LOAD

FIRST 600 MW NUCLEAR UNIT

SECOND 600 MW NUCLEAR UNIT

CUSTOMER LOAD-DURATION CURVE

F, PROBABILITY (P,)

0.75

0.50

0.25

0.00

0.00 250 500 750 1000 1250 1500 1750 2000

P, SYSTEM LOAD (MW)

NON-NUCLEAR CAPACITY
where

\[ P_r = \text{estimated probability reactor } r \text{ is capable of generating energy at random instant of time} \]

\[ T_{rc}' = \text{length of irradiation cycle } c \text{ for unit } r, \text{ hours} \]

\[ K_r = \text{rated electric capacity of unit } r, \text{ MW} \]

If \( T_{rc}' \) was constant, the cycles energies to the horizon were the same and reactor steady-state fuel costs could be calculated and used for all cycles.

However, as nuclear capacity on the system increased, two problems became apparent. First, not all nuclear units could be base-loaded if total nuclear capacity was greater than the minimum load (see Figure 1.2). Equation (1.8) was no longer easily evaluated because the nuclear portion of the load-duration curve was no longer equal to 1.0 for all nuclear units \( (L_r' = ? < 1) \). Which nuclear unit should occupy the base-load position? Intra-nuclear incremental cost competition had surfaced for the first time. Only rough estimates of nuclear fuel costs had been necessary to decide that all nuclear equipment was cheaper than all fossil equipment (22), but very refined costs were now needed to decide nuclear unit A versus nuclear unit B.

Secondly, annual refueling created scheduling problems when each nuclear unit had to be refueled within every calendar scheduling window. Coupled with decreasing nuclear load demand, what was the optimum cycle length for each reactor?
The net result was that cycle energies were no longer easily specified out to the horizon. The nuclear complications rendered previous utility system optimization models obsolete. The nuclear power management model put forth here was developed to provide a modern utility system optimization model capable of handling nuclear plants explicitly. In a utility system containing nuclear powered generating equipment, the planning of the fuel management must be optimized from the system demand viewpoint (cost to utility of supplying all customer loads), not an individual reactor supply viewpoint (cost to utility of supplying power from a particular reactor). The complex interaction between system load and incremental operating costs of the multiplicity of generating units available on a utility system must be considered in optimizing the two nuclear reload design variables—fuel enrichment and batch fraction. The result is that what may appear uneconomical for a particular reactor (e.g., refueling while energy potential remains in the core), may indeed be optimum for the overall system.

1.5 A Nuclear Power Management Multi-year Model

A nuclear power management multi-year model currently under development (23, 34, 41, 55) contains four sub-models as presented in Figure 1.3. The overall model's purpose is to supply the utility system planner with the following outputs:
Figure 1.3
Nuclear Power Management
Multi-Year Model

REFUELING AND MAINTENANCE MODEL (RAMM)

SYSTEM INTEGRATION MODEL (SIM)

$FOSSIL \quad E_{FOSSIL} \quad E_{NUCLEAR}

SYSTEM OPTIMIZATION MODEL (SOM)

$NUCLEAR

CORE SIMULATION AND OPTIMIZATION MODELS (CORSOMs)

$NUCLEAR

OPTIMUM REFUELING, MAINTENANCE AND PRODUCTION SCHEDULE MINIMUM TOTAL COST
(1) Optimum schedule for fossil maintenance and nuclear refueling,
(2) Associated optimum production schedule and
(3) The resultant fuel requirements.

Operation of the overall model begins within the Refueling and Maintenance Model (RAMM). Incorporating such inputs as load forecasts, maintenance requirements and scheduling constraints, the RAMM determines a number of feasible multi-year refueling and maintenance schedules. Each schedule is a mutually exclusive, alternative mode of operating the entire system over the multi-year horizon. The purpose of the rest of the overall model is to determine which of the possible alternative strategies results in the minimum total operating revenue requirement ORR.

The output of the RAMM is accepted by the System Integration Model (SIM) in the form of either a set of downtime dates for each unit on the system or a period-by-period (on the order of one to four weeks per period) maintenance schedule indicating which units are down in each period. Also helpful to the rest of the model is an a priori RAMM ranking of the strategies in order of estimated desirability. That is, "ballpark" estimates by the RAMM of economics and reliability ought to indicate Strategy 1 is most likely to be optimum, while Strategy n (n~100), though feasible, is highly unlikely to be economically attractive and/or a reliable operating scheme. Such a ranking would decrease computing
requirements for the overall model by permitting the detailed evaluation of only those strategies with a reasonable chance of competing for the optimum.

Strategy-by-strategy evaluation begins in the System Integration Model (SIM). For each strategy, the SIM integrates the utility's available equipment, operating practices, etc. into a realistic utility simulation model. Since nuclear incremental costs are much less than those of fossil units, production scheduling is optimized so as to meet customer load demand by maximizing nuclear energy and minimizing fossil energy and fossil cost.

The task of the System Optimization Model (SOM) is to then optimize the operation of the nuclear portion of the system (see Figure 1.3) so that the nuclear energy $E_{\text{Nuclear}}$ is produced at minimum cost, $S_{\text{Nuclear}}$. To do this, the SOM postulates reactor-by-reactor multi-year production schedules which are then passed to Core Simulation and Optimization Models (CORSOM's) for each reactor unit or type (PWR, BWR, LMFBR, etc.). With each production schedule specified to the horizon, each CORSOM is then able to optimize its reload parameters of batch size and enrichment, minimizing the total fuel revenue requirement for the particular reactor. In addition, the CORSOM calculates nuclear incremental costs for each of the cycles.

With all reactors optimized for the given energy production schedules, the SOM begins a second iteration by using the CORSOM's incremental nuclear energy costs to postulate
a better reactor-by-reactor multi-year production schedule.

At each iteration between SOM and the CORSOM's in Figure 1.3, each CORSOM accepts a new set of cycle energies (E's) for its reactor and, in point of fact, the same set of cycle lengths (T's) associated with the particular possible alternative strategy. After simulating core physics-depletion and optimizing the reload parameters (batch size and enrichment), only two specific types of information are returned to the SOM:

1. the minimum total reactor fuel revenue requirement (TCr) and
2. the λrc(Erc) nuclear incremental cost curve for each reactor reload batch,

\[ \lambda_{rc}(E_{rc}) = \frac{\partial TC_r}{\partial E_{rc}} \]  

Specific information about the fuel designs is not needed by the SOM. As long as each CORSOM is properly matched with the reactor unit that it represents, the SOM does not care which units are PWR's, BWR's, HTGR's or fast breeders. Of course, management personnel need fuel design information and it must, therefore, be available in the printed output received directly from the CORSOM (at least, for the final fully-converged iteration).

Iterations between SOM and the CORSOM's continue until the system-wide production schedule converges (see Figure 1.3),
giving minimum system nuclear cost $Nuclear. The total system cost for the particular refueling and maintenance strategy under investigation is then merely the sum of $Fossil and $Nuclear.

After evaluating all possible alternative strategies in this manner, the overall optimum system strategy is the one resulting in the minimum total system operating revenue requirement ORR.

Though the above discussion and, in fact, this entire work assumes only fossil and nuclear equipment exist on the system, the general structure of the overall model holds even if hydro and pumped-hydro equipment have been installed.

The development of the complete nuclear power management multi-year model is a very large task. The four sub-models represent convenient building blocks suitable for somewhat independent development. However, model interface problems must be considered. Ideally, the models ought to be coupled together like the boxcars of a train, not nailed together like the tracks.

In the context of the Commonwealth Edison-sponsored utility system optimization research project at the Massachusetts Institute of Technology, development of a RAMM was assumed by the project sponsor (20). Development of a pressurized water reactor CORSOM was undertaken at MIT by Kearney (41) and Watt (55). The work reported here deals specifically with the development of the remaining SIM and
In this regard, Figure 1.4 and the following sections describe these two models.

1.6 The System Integration Model (SIM)

The System Integration Model (SIM) has as its basic purpose the simulation of multi-year utility operation. To do this, it must integrate the following information into a representative utility system model:

(1) Forecasts of customer loads,
(2) Generating equipment characteristics,
(3) Forecasts of fuel costs,
(4) Maintenance schedules, and
(5) Operating constraints.

To portray system operation more accurately, the multi-year horizon is divided into much smaller time periods, on the order of a few weeks. Periods shorter than a week create an undue computational burden. On the other hand, periods longer than a month are precluded by the necessity of discretely representing scheduled maintenance outages which are usually two to four weeks in length.

These time periods are then simulated individually in chronological sequence. Forecasted loads for each period (Item 1 above) are represented by a normalized customer load-duration curve. Thermal energy costs (Item 3) are combined with the characteristics of the generating units to yield unit incremental costs. Any units unavailable due to scheduled maintenance (Item 4) are treated as non-existent for
Figure 1.4 NUCLEAR POWER MANAGEMENT MULTI-YEAR MODEL
that period. The next step is the establishment of the startup and loading order for the remaining (on-line) units. It is in this order that various operating constraints (Item 5), such as "spinning reserve" and "zone-loading" requirements are incorporated. Production scheduling of the resulting system representation is performed using the Booth-Baleriaux (10, 19) probabilistic utility system model.

As pointed out earlier (see Section 1.4), the complexities of nuclear power preclude \textit{a priori} knowledge of nuclear fuel costs except for the special case of all nuclear base-load operation. Nevertheless, by incorporating nuclear versus fossil incremental cost arguments (22) to sub-optimize each period, the SIM is able to mark time by calculating in its place, the system nuclear potential (demand) $N$ for each period (a part of the horizon's total $E_{\text{Nuclear}}$). The responsibility for optimizing and costing intra-nuclear production of this energy rests with the System Optimization Model (SOM).

Thus, the actual period-by-period output of the SIM consists of:

(1) $X_F$ = Fossil fuel expense related to energy production,

(2) $N$ = Potential nuclear energy production,

(3) $X_S$ = Combined fossil and nuclear startup-shutdown cost, and

(4) $X_U$ = Expense related to emergency energy purchases.
1.6.1 Booth-Baleriaux Probabilistic Utility Simulation Model

The Booth-Baleriaux probabilistic utility simulation model is a recent adaptation of previous deterministic utility models with new emphasis on the field of applied probability theory. Though the original 1967 paper on the subject is a product of Baleriaux, et al., (10) of Belgium, Booth (17-19) of Australia deserves much of the credit for introducing and promoting the model in the United States.

Previous papers reporting on the Booth-Baleriaux model, including the work of Joy and Jenkins (39), have closely followed the development in the original paper. With due respect to these ground-breaking efforts, the following presentation leads to computational savings in terms of time and storage, and also follows a more direct line of reasoning.

The Booth-Baleriaux probabilistic utility model is based on the concept of equivalent system load which embodies not only direct customer demands on a particular unit, but also the indirect demands left unsatisfied by previously loaded units when they are on forced-outages.

The equivalent load \( P_e \) may be defined as

\[
P_e = P_D + P_O
\]

where

\( P_D \) = actual direct customer load demand, MW
\[ P_O = \text{system capacity on forced-outage that would be generating energy otherwise, MW} \]

Capacity that is on forced-outage during what would otherwise have been reserve (i.e., economy) shutdown hours anyway is not counted since the outage does not affect system generating operations.

In a probabilistic sense, \( P_D \) is a random variable with a complementary cumulative distribution given by \( F_D(P_D) \), the normalized customer load-duration curve. Since forced-outages are random, \( P_O \) is also a random variable characterized by the performance probabilities of each unit. Thus, \( P_e \) is also a random variable and the computation of its complementary cumulative distribution (the equivalent load-duration curve) \( F_e(P_e) \) involves the convolution (26) of the distributions of \( P_D \) and \( P_O \). The heuristic presentation here is limited to the common two-state model of forced-outages:

State 1: With performance probability \( p \), the unit will perform at any output up to its rated capacity when called upon, and

State 2: With non-performance probability \( q \), the unit will not perform at all when called upon.

Thus,

\[ p + q = 1 \quad (1.11) \]

In accounting for the forced-outages of all of the utility's available generating units (i.e., those not down
anyway due to scheduled outages), the approach presented in this work performs the system-wide convolution by sequentially incorporating each unit's contribution to the equivalent load. Referring to Figure 1.5, the general equation for convolving up to the $i$th increment of unit $r$ into the equivalent load-duration distribution $F_{ri}^{WO}$ can be shown to be as follows,

$$F_{ri}^{W}(P_e) = p_r F_{ri}^{WO}(P_e) + q_r F_{ri}^{WO}(P_e - K_{ri})$$

for all $P_e$

where

- $F_{ri}^{W}$ = Equivalent load distribution with the forced-outages of $i$ increments of unit $r$ included.
- $F_{ri}^{WO}$ = Equivalent load distribution without the forced-outages of $i$ increments of unit $r$ included.
- $K_{ri}$ = Rated capacity of unit $r$ up to and including $i$th increment, i.e., magnitude of forced-outage included in $P_e$ when forced-outage occurs ($q_r$ fraction of the time), MW
- $p_r$ = Performance probability of unit $r$.
- $q_r = 1 - p_r$

Due to Equation (1.10), $K_{ri}$ may be less than the $K_r$ maximum rated capacity of unit $r$ because the rest of the unit's capacity is not being used whether on forced-outage or not.
Figure 1.5
Convolution of Unit $r$

- $F^W_{ri}(P_e-K_{ri})$
- $F^W_{ri}(P_e)$

$w_0 =$ WITHOUT INCLUSION OF
UNIT $r$'S FORCED-OUTAGES
$w =$ WITH

MINIMUM CUSTOMER LOAD

$F_r$, PROBABILITY ($P_r \geq 0$) OR FRACTIONAL DURATION

SYSTEM EQUIVALENT LOAD
Since Equation (1.12) is valid for all $P_e$, (not merely the single value shown in Figure 1.5), the complete $F_{ri}^w(P_e)$ curve can be calculated easily. Two limiting cases are readily apparent. One case is $P_e$ less than the minimum load—each $F_{ri}^{wo}=1$, as does the resulting $F_{ri}^w(P_e)$. For very large $P_e$, each $F_{ri}^{wo}=0$ and, hence, $F_{ri}^w(P_e)=0$. Equation (1.12) is the heart and soul of the Booth-Baleriaux model. All subsequent calculations involving $F$, whether convolutions or deconvolutions (see below) are merely rearrangements of it.

Deconvolution merely refers to reversing the convolution process, subtracting unit $r$'s forced-outages from the equivalent load. That is, given $F_{ri}^w(P_e)$, determine $F_{ri}^{wo}(P_e)$. The necessity of performing deconvolutions comes about because:

(1) entire units are not scheduled as single blocks of capacity but as smaller capacity increments due to units' varying incremental costs, and

(2) during the production calculation (see below), increments of the same unit cannot possibly make up for each other's forced-outages since they are all forced offline together (at least, in the simple two-state forced-outage model).

Rearranging Equation (1.12) to the following, deconvolution is accomplished thusly,

$$F_{ri}^{wo}(P_e) = \frac{1}{pr} \left[ F_{ri}^w(P_e) - q_r F_{ri}^{wo}(P_e - K_{ri}) \right]$$

(1.13)
Making use of the fact that $F^{\text{WO}}_{ri}(P_e) = 1$ for $P_e$ less than the minimum load, $F^{\text{WO}}_{ri}(P_e)$ can be "boot-strapped" from right to left in Figure 1.5 to determine the complete $F^{\text{WO}}_{ri}$.

As illustrated in Figure 1.6, forced-outages of units lower in the loading order increase the demand or duration of load [$F^{\text{WO}}_{ri}(P_e) > F_D(P_e)$] to be satisfied by capacity increments higher in the loading order. However, forced-outages affect not only the demand $F^{\text{WO}}_{ri}$ on each increment, but also the increment's energy production $E_{ri}$. If the unit only performs 90% of the time, then it is expected that only 90% of the production demanded from it will be served. Recalling that $p_r$ is the unit's performance probability, the increments' expected energy production for the period is given by,

$$E_{ri} = T' p_r \int_{P_{ri}^*}^{P_{ri}^* + \Delta K_{ri}} F^{\text{WO}}_{ri}(P_e) dP_e$$

(1.14)

where

- $T' =$ duration of time period, hours
- $\Delta K_{ri} =$ $i$th increment of capacity of unit $r$, MW
- $P_{ri}^* =$ system equivalent load when increment $i$ first loaded, i.e., the increment's loading point.

Total unit energy production for the period, $E_r$, is given by summing $E_{ri}$ over the unit's I increments,

$$E_r = \sum_{i=1}^{I} E_{ri}$$

(1.15)
Figure 1.6

Determining Energy Demand on Increment $i$ of Unit $r$

$F$, PROBABILITY ($P_e > 2$)

$F_D$ (WITH ENTIRE SYSTEM CONVOLVED INTO $F_D$)

$K_T^I$ AVAILABLE INSTALLED CAPACITY

LOLP

$\Delta K_{ri}$

$D_V$

$P_e$, SYSTEM EQUIVALENT LOAD

$P_{ri}^o$ $P_{ri}^o + \Delta K_{ri}$
At an average cost of \( \bar{e}_{rl} \) for the first increment and incremental costs \( \lambda_{ri} \) for the other increments, the cost of each energy increment is

\[
X_{rl} = \bar{e}_{rl} E_{rl} \quad (1.16)
\]

\[
X_{ri} = \lambda_{ri} E_{ri} \quad \text{for } i > 1 \quad (1.17)
\]

and, hence, period production fuel expense \( X_r \) for unit \( r \) is given by

\[
X_r = \sum_{i} X_{ri} \quad (1.18)
\]

Recall from Section 1.6, that for nuclear units, the SIM's required period output is not cost, but the system nuclear potential \( N \),

\[
N = \sum_{\text{Nucl. Units}} E_r \quad (1.19)
\]

In Figure 1.6, notice that for the final total system curve, \( F_T \), some indirect customer demand extends beyond the available installed (on-line) capacity,

\[
K'_T = \sum_{\text{On-line Units}} K_{rI} \quad (1.20)
\]
As one measure of system reliability, $D_U$ represents the energy unserved by the system's resources \(\text{i.e., wholly owned capacity plus firm purchases,}\)

$$D_U = T' \int_{K'_T}^{\infty} F_T(P_e) dP_e$$ \hspace{1cm} (1.21)

"Expected unserviced energy . . . is the expected curtailment or, more realistically, the expected emergency support required during" the time period (49). The determination of the $X_U$ expenditure relative to the $D_U$ emergency electricity purchases from neighboring utilities is straightforward given an $\bar{e}_U$ average cost for this emergency support. The period expenditure is merely,

$$X_U = \bar{e}_U D_U$$ \hspace{1cm} (1.22)

Along with $D_U$, another measure of the system's reliability is the LOLP "loss-of-load-probability,"

$$\text{LOLP} = F_T(K'_T)$$ \hspace{1cm} (1.23)

the fraction of time the utility is unable to serve its customers with its own resources.
With production scheduling completed, only the task of determining the startup-shutdown cost component for the period remains. To accurately calculate the period's $X_S$, startup-shutdown cost, an hour-by-hour production scheduling model would be required. Having sacrificed detailed chronological load shapes for the more convenient load-duration curves covering much longer periods of time, shutdown costs must be estimated by an approximate technique.

Consider Figure 1.7 [after (18)] which displays qualitatively the approximate relation between $\Omega$, the frequency of startup-shutdowns (per day) and $L'_{rl}$, the availability-based capacity factor for the unit's first capacity increment. That is,

$$L'_{rl} = \frac{1}{K_{rl}} \int_{P_{rl}}^{P_{rl}^*} \frac{K_{rl}}{F_{rl}(P_e) dP_e} \quad (1.24)$$

For must-run units, $L'_{rl}$ equals 1 and $\Omega$ equals 0. For very expensive peaking units, $L'_{rl}$ approaches 0 and $\Omega$ again approaches 0. As expected, units never shutdown and units never started-up incur no startup-shutdown cost. In between are those units started-up and shutdown on a daily basis and, hence, $\Omega$ approaches one.

If unit startup-shutdown cost $Q_r$ is specified in time independent units of equivalent thermal energy input, multiplying it by $\phi_r$, the unit's thermal energy cost for the period,
Figure 1.7

Example of Startup-Shutdown Frequency versus Availability-Based Capacity Factor [After (18)]
permits escalation in terms of undiscounted dollars. Since L'\textsubscript{rl} is easily extracted for each unit during the Booth-Baleriaux simulation, the fractional starts per day are easily estimated given the proper dependence of \( \Omega \) upon L'\textsubscript{rl}. Thus, a period T'/24 days long, incurs total period startup-shutdown cost amounting to

\[
X_S = \frac{T'}{24} \sum_{r}^{R} \phi_r Q_r \Omega(L'_r) \tag{1.25}
\]

1.6.2 SYSINT, A Computerized Version of the SYStem INTegration Model

SYSINT, a 2000 card Fortran IV version of the SYStem INTegration Model is detailed in Appendix E. This section merely summarizes its capabilities.

The standard two-state forced-outage model (perform or not perform) is employed. A single startup frequency curve \( \Omega(L'_r) \) is input for the entire horizon. The limitations of the current version, though easily altered, are as follows:

1. up to 100 units (including retirements and additions),
2. up to 5 valve points for each unit,
3. no limit on number of strategies per computer run,
4. up to 100 time periods per strategy and
5. up to 25 typical load-duration "shapes," stored in completely normalized form (i.e., peak demand also equals one.)
The multi-period strategy is input for each unit in the following form:

(1) the period installed,
(2) period just prior to retirement and
(3) up to 20 intermediate periods of downtime for maintenance or refueling.

For each period the following data may be input or altered:

(1) Choice of load-duration shape,
(2) Forecasted peak demand,
(3) Expected spinning reserve requirement,
(4) Length of time period,
(5) Average cost of emergency purchase energy,
(6) Fuel cost for each unit (optional initial guess for nuclear units),
(7) Performance probability for each unit, and
(8) Startup order indicating must-run units and peaking equipment.

As for typical running time, each period of a simulation of a utility system containing 40 units with a total of 150 valve points requires approximately 2.5 CPU sec on an IBM 370 Model 155 computer operating in an MVT environment. The code itself requires 108 K bytes of storage, i.e., not including the computer system supervisor. Total core requirements are thus approximately 134 K bytes.

Data transfer from SYSINT to SYSOPT (see Section 4.6 and Appendix F) is completely automated via either disk,
magnetic tape or punched cards.

1.7 System Optimization Model (SOM)

The SOM receives period-by-period information from the SIM relative to the system nuclear energy production potential and each reactor's possible maximum (i.e., if it is the first nuclear unit to be loaded) and minimum (i.e., if last nuclear unit) contribution to it. In addition, the non-nuclear cost totals are entered and later discounted at the appropriate present value rate to yield the total non-nuclear revenue requirement. Optimization itself (see Figure 1.4) begins by utilizing any initial nuclear fuel cost estimates to schedule period-by-period, reactor-by-reactor energy production using network programming (NP).

1.7.1 Nuclear Supply Network Optimization

Since the optimization within the SOM deals with a single commodity (nuclear energy production) in a strict one-to-one (reactor) supply and (customer) demand sense, the production constraints form a (nuclear energy) supply network. Figure 1.8 presents such a network configuration for a 3 reactor, 24 period (month) example. Numbers are displayed for the nuclear potentials $N_p$ to emphasize the fact that these are fixed constraints throughout all of the iterations for a particular refueling and maintenance strategy. Nuclear energy is allocated (i.e., supplied) to each reactor-cycle ($E_{rc}$). Within each cycle, this energy is allocated to the pertinent
Figure 1.8

Sample Network Configuration

<table>
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<tr>
<th>PERIOD</th>
<th>REACTOR 1 CYCLE:</th>
<th>REACTOR 2 CYCLE:</th>
<th>REACTOR 3 CYCLE:</th>
<th>NUCLEAR POTENTIAL, Mp</th>
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</table>
periods \((E_{rcp})\) so as to satisfy the system nuclear potentials (i.e., demanded).

The objective function for the nuclear supply network optimization is the system nuclear fuel revenue requirement,

\[
\text{minimize } \quad RR_N \equiv \bar{TC} = \sum_{\text{all } r} \bar{TC}_r(E_{r1}, E_{r2}, ...) \quad (1.26)
\]

Due to the nonlinearity of Equation (1.26) as discussed in Section 1.4, an iterative gradient optimization technique known as the "method of convex combinations" (54) is employed. With the gradient defined as \(\lambda_{rc}\), the incremental cost (revenue requirement) of extracting an additional amount of energy in cycle \(c\) of reactor \(r\), then

\[
\lambda_{rc} = \frac{\partial \bar{TC}_r}{\partial E_{rc}} \quad (1.27)
\]

Denoting the iteration or trials by the superscript \(t\), a Taylor expansion of the objective function about the "current" \(t\) set of reactor-cycle energies yields,

\[
\text{minimize } \quad \bar{TC}^{t+1} = \bar{TC}^t + \sum_{\text{all } r} \sum_{\text{all } c} \int_{E_{rc}}^{E_{rc}^{t+1}} \lambda_{rc}(E_{rc}) dE_{rc} \quad (1.28)
\]
Thus, given the information at the t th iteration, the next iteration determines the t+1 set of \( E_{rc} \) so that the double summation term of Equation (1.28) is minimized subject to the constraints indicated in Figure 1.8. Specifically, the sum of any column must equal the energy supplied (or extracted) during that particular reactor-cycle,

\[
E_{rc} = \sum_{p \in c} E_{rcp} \quad \text{for all } r \text{ and all } c \quad (1.29)
\]

At the same time, the sum of any row must equal the period's required nuclear potential,

\[
N_p = \sum_{r} E_{rcp} \quad \text{for all } p \quad (1.30)
\]

The range of each \( E_{rcp} \) is also constrained ("capacitated") via

\[
E_{min}^{rcp} \leq E_{rcp} \leq E_{max}^{rcp} \quad \text{for all } r \text{ and all } p \quad (1.31)
\]

which is indicative of the minimum and maximum demand in the equivalent load range served by the nuclear units. Representative \( E_{min}^{rcp} \) and \( E_{max}^{rcp} \) for each \( E_{rc} \) in Figure 1.8 are presented in Table 1.2.

At each iteration, the \( E_{rc} \) cycle energy production requirements are passed to the CORSOM's which design the fuel reload batches (batch size and enrichment) to meet the
### Table 1.2

**Reactor Production Limits for 3 Reactor, 24 Period Example**

<table>
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<th>Reactor 2</th>
<th>Reactor 3</th>
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<td>$E_{\text{max}}^{1\text{cp}}$</td>
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All $E_{\text{rcp}}$ in GWH
production schedule and refueling dates at minimum reactor cost. Information returned to the SOM is minimum total reactor nuclear fuel revenue requirement $\overline{TC_r}$ (for later summation of total system nuclear costs) and the nuclear incremental cost curve of each reload batch,

$$\lambda_{rc}(E_{rc}) = \frac{\partial \overline{TC_r}}{\partial E_{rc}} \quad (1.32)$$

With these incremental costs, the network algorithm reoptimizes nuclear production in order to minimize the objective function [Equation (1.28)]. The result is that all nuclear reload batches are designed at the same incremental cost within the limits of availability and loads (22).

To illustrate a single iteration, consider the 3 reactor, 24 period example of Figure 1.8 and Table 1.2. Figure 1.9 presents a hypothetical set of incremental cost curves returned to the SOM at the end of the previous iteration. The "stair-step" nature of the curves is indicative of the piecewise-linearization of $\overline{TC}$ required to cast the double summation term in Equation (1.28) in an NP format. Note that the NP program effectively seeks to establish equal incremental costs among the reactor-cycles that compete for the nuclear potential (e.g., at the optimum, $\lambda^*_{1,1} = \lambda^*_{2,2} = \lambda^*_{3,1}$). Figure 1.10 presents the complete, optimized period-by-period reactor production schedule for this example.
Figure 1.9

Hypothetical Set of Incremental Cost Curves

\[ \lambda_{rc} \text{ INCREMENTAL COST} (\$/MWH) \]

\[ E_{rc} \text{ CYCLE ENERGY} (10^3 \text{ GWH}) \]

- \( \triangle - E_t^{rc} \)
- \( \circ - E_{t+1}^{rc} \)

\[ r.c = 1.2 \]

\[ E_{2,1} + 5000 \]
Sample Reactor Production Schedule

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<tr>
<th>PERIOD</th>
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<th>REACTOR 3 CYCLE:</th>
<th>NUCLEAR POTENTIAL, Np</th>
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<td>15</td>
<td>752</td>
<td>571</td>
<td>686</td>
<td>2009</td>
</tr>
<tr>
<td>16</td>
<td>758</td>
<td>REFUELLING</td>
<td>706</td>
<td>1464</td>
</tr>
<tr>
<td>17</td>
<td>761</td>
<td>687</td>
<td>657</td>
<td>2105</td>
</tr>
<tr>
<td>18</td>
<td>762</td>
<td>704</td>
<td>686</td>
<td>2152</td>
</tr>
<tr>
<td>19</td>
<td>763</td>
<td>719</td>
<td>724</td>
<td>2206</td>
</tr>
<tr>
<td>20</td>
<td>762</td>
<td>704</td>
<td>686</td>
<td>2152</td>
</tr>
<tr>
<td>21</td>
<td>762</td>
<td>704</td>
<td>686</td>
<td>2152</td>
</tr>
<tr>
<td>22</td>
<td>758</td>
<td>674</td>
<td>643</td>
<td>2075</td>
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<td>759</td>
<td>671</td>
<td>632</td>
<td>2062</td>
</tr>
<tr>
<td>24</td>
<td>REF</td>
<td>722</td>
<td>743</td>
<td>1465</td>
</tr>
</tbody>
</table>

HOLDOVER: 2500 REF 2500

TOTAL: 9150 6837 1442 8350 8085 7401 8372 49,637 GWH
In addition to the above network constraint Equations (1.30) and (1.31), which are special cases of linear constraints and can therefore be handled easily by a standard NP code (45), a nonlinear constraint for each period must also be incorporated. In particular, after the iterations are complete, a check must be made to ensure that the optimum $E_{rcp}$ reactor-period energy productions are compatible, or feasible, with regard to shape of the period's equivalent load curve. As illustrated in Figure 1.11, even though Equation (1.30) is satisfied, the set of energy productions for the four nuclear units is not feasible. Within that segment of the equivalent load curve preassigned to the nuclear units (i.e., after the must-run fossil units), the low minimum load permits only one unit A or B to operate as a base-load unit.

In order to account for this feasibility problem, a shape constraint (similar to a least-squares fitting criterion) was derived that of necessity, included second-order terms in $E_{rcp}$:

$$\sum c_{1 rp} \cdot E_{rcp} + \sum c_{2 rp} \cdot E_{rcp}^2 \leq c_p$$  \hspace{1cm} (1.33)$$

The $c_{1 rp}$, $c_{2 rp}$ and $c_p$ are constants for each reactor $r$ in period $p$, precalculated by the SOM using the nuclear segment.
Example of Infeasible Equivalent Load Shape

INFEASIBLE ATTEMPT TO SATISFY NUCLEAR PORTION OF EQUIVALENT LOAD CURVE SHAPE EVEN THOUGH AREAS EQUAL BELOW TWO CURVES (cf. NUCLEAR ENERGY $N_p = \text{CONSTANT}$)

MINIMUM LOAD

ABUNDANT HYDRO OR MUST-RUN FOSSIL UNITS

NUCLEAR UNIT A

NUCLEAR UNIT B

NUCLEAR UNIT C

NUCLEAR UNIT D

REMAINING FOSSIL UNITS

$F_e$, PROBABILITY ($P_e \geq$)

$P_e$, EQUIVALENT LOAD
of the actual equivalent load curve and the performance characteristics of the various nuclear units.

As mentioned above, the nonlinear shape constraint is implemented as a posterior check on the optimized reactor-period production schedules. For each period violating the shape constraint Equation (1.33), the $E_{\text{min}}^{\text{rcp}}$ and $E_{\text{max}}^{\text{rcp}}$ of each reactor's production constraint Equation (1.31) are "squeezed" slightly toward their mean so that infeasible schedules (such as in Figure 1.11) are unlikely to occur in that period again. After checking and adjusting the production constraints for all infeasible periods, the revised network is again optimized. Such shape iterations continue until all periods of an optimized schedule satisfy their respective shape constraint.

When iterative convergence and feasibility of the production schedule is realized, overall fossil-nuclear system operation has been optimized for the particular possible alternative maintenance and refueling schedule under investigation.

With the optimization task completed, the resulting (minimum) $\overline{TC^*}$ represents the total revenue requirement for nuclear fuel $RR_N$. By present-valuing all of the other period expenditures (received as input from the SIM) according to Equation (1.3), the determination of ORR is complete,

$$\text{ORR} = RR_N + \sum_{t=0}^{T} \frac{1}{(1+x)^t} \left( X_{F_p} + X_{S_p} + X_{U_p} \right)$$ (1.34)
The ORR operating revenue requirement is appropriately stored for later comparison with that of other possible alternative strategies. With the completion of this task, processing of the particular alternative refueling and maintenance strategy is complete. And with completion of the last alternative strategy, selection of the minimum ORR cost strategy becomes possible.

1.7.2 SYSOPT, A Computerized SYStem OPTimization Model

SYSOPT, a 2100 card Fortran IV version of the SYStem OPTimization Model is detailed in Appendix F. SYSOPT is link-edited with the Out of Kilter Network Program (45) which represents an additional 1200 cards in Fortran IV and Assembler Language. Out of Kilter is detailed in Appendix G. This section merely summarizes the capabilities of the current combined version of SYSOPT.

The limitations of the current version of SYSOPT, though easily altered, are as follows:

(1) up to 15 reactors,
(2) up to 15 cycles per reactor within the horizon,
(3) up to 3 cycles per reactor beyond the horizon,
(4) no limit on number of strategies per computer run, and
(5) up to 100 periods per strategy.

Input data for each strategy includes:

(1) Present value rate,
(2) Various convergence criteria, and
(3) Maximum number of iterations to be permitted.

Input data supplied manually for each reactor includes:

(1) Optional initial estimates of $\lambda_{rc}^*$ or $E_{rc}^*$,

(2) Holdover energy at end of planning horizon, and

(3) Cycle energies and refueling dates beyond planning horizon.

The large volume of SYSINT output required by SYSOPT may be passed either on disk, magnetic tape or punched cards.

As for typical running times on an IBM 370 Model 155 computer (MVT environment), a hypothetical six reactor utility required only 9 CPU seconds per inner iteration (exclusive of time spent in CORSOM's) for strategies 72 periods long and totaling 30 reactor-cycles. The SYSOPT code itself requires 130 K bytes of storage (plus ~26 K for computer supervisor), while the Out-of-Kilter Network Program requires an additional 135 K. Using an overlay structure reduces the 265 K total to 200 K. Execution time is not noticeably increased by the use of the overlay structure.

1.8 Model Evaluation

To properly evaluate the SIM and SOM (or more specifically, the computerized versions SYSINT and SYSOPT, respectively), required interfacing them with a RAMM and CORSOM's to complete the nuclear power management multi-year model of Figure 1.3.

For the purposes of developing and testing a SIM and SOM, the multitude of possible alternative strategies output by a
RAMM were replaced by a few typical strategies developed through simple hand calculations. On the other hand, the on-line iterative nature of the optimization procedure requires computerized CORSOM's. The state of the art, as witnessed by the concurrent methods development research by Kearney (41) and Watt (55), precluded utilization of an established multi-year CORSOM. In order to proceed with the testing of the SIM and SOM, QKCORE, a psuedo-one dimensional, quick core model (performing simulation only), was developed (see Appendix H). The nature of QKCORE necessarily limited the scope of the evaluation to LWR's with the following characteristics:

1. Modified-scatter refueling with fixed number of zones (e.g., refueling fraction was fixed at one-third),
2. No plutonium recycle,
3. No stretchout beyond reactivity-limited energy, and
4. No cycle-to-cycle optimization
   (i.e., at each refueling, minimum enrichment chosen regardless of future cycles).

To evaluate the model's usefulness, several sample cases were calculated. An electric utility possessing six 1050 MW PWR's on a 46-unit 11,000 MW system was hypothesized. Minimum customer loads (typically 4000 MW), combined with other system operating constraints, restricted average nuclear availability-based capacity factors to about 80 per cent, i.e., below base-load operation.
Three possible refueling strategies were investigated:
S-1: strictly annual refuelings
S-2: gradual shift to longer (14 month) cycles
S-3: immediate shift to the longer cycles with
additional cost of one million dollars for each
short notice enrichment change.

Underlying later discussion of the choice from among the
several optimized strategies are the properties of the indi-
vidual strategies themselves. The important numerical proper-
ties are convergence, incremental costs and computational
requirements. The results (see Table 1.3) of Strategy 2 over
a six year horizon will be used for most of the discussion.
However, when this Strategy fails to clearly demonstrate a
point under discussion, one of the other two will be utilized.

1.8.1 Convergence

Starting from a relatively poor initial guess of equal
energy in each cycle regardless of cycle length, the opti-
mization of S-2 required ten cost iterations to converge to
the initial optimum \( TC^* \). The iteration-by-iteration system
nuclear fuel cost \( TC^t \) (i.e., the objective function of the
optimization) in presented in Figure 1.12. Since initially
50% of the 72 periods failed their shape constraint, three
more iterations were required to produce the feasible
optimum. This resulted in a cost increase of only 0.25 (out
of nearly 300) million dollars.
Table 1.3

Revenue Requirements and Undiscounted Energy for Accepted Global Optimum of Strategy 2 over Six Year Horizon

<table>
<thead>
<tr>
<th></th>
<th>$10^6$</th>
<th>$10^6$ MWH</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fossil Fuel</strong></td>
<td>276.583</td>
<td>85.836</td>
</tr>
<tr>
<td><strong>Startup-shutdown Cost</strong></td>
<td>1.704</td>
<td>--</td>
</tr>
<tr>
<td><strong>Emergency Purchases</strong></td>
<td>0.407</td>
<td>0.048</td>
</tr>
<tr>
<td><strong>Non-nuclear Production</strong></td>
<td>278.964</td>
<td>85.884</td>
</tr>
<tr>
<td><strong>Nuclear Fuel</strong></td>
<td>297.709</td>
<td>194.077</td>
</tr>
<tr>
<td><strong>System Production</strong></td>
<td>576.673</td>
<td>279.961</td>
</tr>
<tr>
<td><strong>Fixed Firm Purchase</strong></td>
<td>133.920</td>
<td>81.468</td>
</tr>
<tr>
<td><strong>System Total</strong></td>
<td>710.593</td>
<td>361.429</td>
</tr>
</tbody>
</table>
Figure 1.12

Convergence of Inner Cost Iterations for Initial Shape Iteration of Strategy 2 in Case 1

$T_{C,t}^{\infty}$, SYSTEM NUCLEAR FUEL REQUIREMENT ($10^6$ $\text{\$}$)

$\Sigma_{t+1}^{\text{ACT}}$

$\Delta = 100 \text{ GWH CONVERGED}$

$\Delta = 20$

$\Delta$ REPARES SIZE OF "STAIR-STEPS" USED TO APPROXIMATE INCREMENTAL COST CURVES
The symbol $\Delta$ in the Figure represents the energy step size used to segment the continuous incremental cost curves into the stair-step cost functions required by the SOM's NP optimization package. As $\Delta$ decreases, the accuracy of the stair-step representation increases as do the computational requirements. Thus, the relatively poor $\lambda_{rc}$ fits at large $\Delta$ were utilized for the initial iterations until either the cycle energies converged (to within a specified percent of $\Delta$, typically 100%) or the objective function itself converged (i.e., the last iteration failed to improve the objective function by more than a required amount, say $\$2000$). In fact, iteration 5 displayed "negative" improvement because piecewise-linearization of $TC_r$ prevented the NP program from seeing the smooth increase of $\lambda_{rc}$ for fractional $\Delta$ changes in cycle energy. The net result was that the NP program over-reacted to small differences between various $\lambda_{rc}$ incremental costs.

After convergence using the first $\Delta$, a second and smaller $\Delta$ was utilized and convergence again attained using the same two criteria. This second converged solution was considered to be the initial optimum $TC^*$. 

From three standpoints, a third $\Delta$ choice appeared unwarranted:

(1) With total nuclear fuel cost approaching $\$300,000,000$ for the six year horizon, the fuel cost improvement from the $\Delta = 100$ GWH optimum solution to $\Delta = 20$ was
only $220,000 for the fivefold $A$ reduction and would undoubtedly have been much less than that for another fivefold reduction.

(2) At $A = 20$ GWH, cycle energies were already converged to well within 1% ($\pm 50$ GWH out of 6000-8000 GWH).

and

(3) The fuel cost errors and cycle energy errors both appear to be well within the noise levels of CORSOM errors ($> 100,000$ per reactor over the planning period) and the errors inherent in forecasting load demands and availabilities ($> 1\%$).

Using the above sequence of the two step sizes, all cases effectively converged (i.e., objective function decreasing insignificantly for $A = 20$ GWH) within ten iterations. Inasmuch as completed CORSOM's are estimated to require over 3 minutes of IBM 370 Model 155 CPU time per reactor strategy per iteration (41), an average six reactor-four iteration solution would involve over an hour and a half of computer time for the CORSOM's alone. The ad hoc simulator QKCORE required less than 3 minutes for all ten iterations.

1.8.2 Nuclear Incremental Costs at the Optimum

An analytical discussion of nuclear utility system optimization similar to that in (22) presents two conclusions relating a strong primary dependence between pertinent cycle incremental costs for each reactor during each period and a
weak secondary conclusion relating an idealized state that may not be attainable:

**Conclusion I:**

At the optimum reactor-cycle energies,

$$
\lambda_{Np} = \frac{\partial TC_r}{\partial E_{rc}} 
$$

for all r (1.35) during each period for the pertinent cycle of each reactor.

**Conclusion II:**

At the optimum reactor-cycle energies,

$$
\lambda_N = \frac{\partial TC_r}{\partial E_{rc}} 
$$

for all periods, all cycles and all reactors simultaneously.

As for typical values of $\lambda_{Np}$ and $\lambda_N$, the results of Widmer (57), Kearney (51) and Watt (55) indicate optimum mid-range nuclear incremental costs in the range of 0.9 to 1.5 $/MWH.

The terms "strong" and "weak" refer to the number of incremental cost violations anticipated because of over-riding engineering and time constraints.

The $\lambda^*_{rc}$ cycle-by-cycle incremental costs at the optimum of Strategy 2 are presented in Figure 1.13. In analyzing these values, four important points are to be made. First, the general equality of $\lambda^*_{rc}$ at each point in time confirms Conclusion I.
Figure 1.13
Incremental Costs and Cycle Energies at Accepted Global Optimum
for Strategy-2 in Case I

<table>
<thead>
<tr>
<th>TIME (YEARS)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Reactor A</th>
<th>0.959</th>
<th>1.309</th>
<th>1.408</th>
<th>1.408</th>
<th>1.408</th>
<th>1.173</th>
<th>1.173</th>
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<td></td>
<td>(5270)</td>
<td>(6720)</td>
<td>(7260)</td>
<td>(7580)</td>
<td>(7775)</td>
<td>(7165)</td>
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</table>

<table>
<thead>
<tr>
<th>Reactor B</th>
<th>0.959</th>
<th>1.309</th>
<th>1.408</th>
<th>1.408</th>
<th>1.408</th>
<th>1.173</th>
<th>1.173</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(6420)</td>
<td>(7566)</td>
<td>(7500)</td>
<td>(8060)</td>
<td>(7732)</td>
<td>(7732)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reactor C</th>
<th>0.959</th>
<th>1.309</th>
<th>1.408</th>
<th>1.408</th>
<th>1.408</th>
<th>1.248</th>
<th>1.248</th>
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<tbody>
<tr>
<td></td>
<td>(6300)</td>
<td>(7260)</td>
<td>(7218)</td>
<td>(7500)</td>
<td>(7480)</td>
<td>(7480)</td>
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<table>
<thead>
<tr>
<th>Reactor D</th>
<th>0.959</th>
<th>1.408</th>
<th>1.408</th>
<th>1.408</th>
<th>1.408</th>
<th>1.070</th>
<th>1.070</th>
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<tbody>
<tr>
<td></td>
<td>(5340)</td>
<td>(7820)</td>
<td>(7460)</td>
<td>(8060)</td>
<td>(7089)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Reactor E</th>
<th>0.959</th>
<th>1.401</th>
<th>1.408</th>
<th>1.244</th>
<th>1.248</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>(7200)</td>
<td>(7623)</td>
<td>(7133)</td>
<td>(8174)</td>
<td>(7855)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reactor F</th>
<th>0.657</th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>(2100)</td>
<td></td>
<td></td>
<td></td>
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</table>
Secondly, incremental costs increase over the first few cycles as the short-range incremental costs of the first year give way to the mid-range incremental costs of later cycles. During the first year, incremental costs are very low because a large proportion of each reactor's cycle costs (e.g., separative work, fabrication and reprocessing) are already spent or committed. Discharge burnup is the only variable. Thus, \( \lambda^{*}_{r1} \) is Widmer's short-range incremental cost \((57, 59)\). For a cycle further into the future, a larger degree of flexibility is available in the design of the reload batch (size and enrichment) and a larger fraction of total cycle costs can thus be altered. For \( c > 2 \), \( \lambda^{*}_{rc} \) becomes Widmer's mid-range incremental cost \((58, 59)\). Thus, short-range incremental costs evolve into mid-range incremental costs.

During the middle two to five years of Strategy 2, the constancy of \( \lambda^{*}_{rc} \) for most reactor-cycles provides ample evidence that Conclusion II is also valid.

Finally, the \( \lambda^{*}_{rc} \) beyond the fifth year are, indeed, optimal (but erratic) due to the assumed horizon end condition which involved specifying cycle energies beyond the horizon in order to permit cost evaluation of the core contents at the horizon.

Though Figure 1.13 confirmed Conclusion II, the typical \( \lambda^{*}_{rc} \) optima of the other strategies did not. For example, Figure 1.14 presents \( \lambda^{*}_{rc} \) for Strategy 1 over the same six
Figure 1.14

Incremental Costs and Cycle Energies at Accepted Global Optimum
for Strategy 1 in Case I

<table>
<thead>
<tr>
<th>REACTOR</th>
<th>TIME (YEARS)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.683</td>
<td>0.992</td>
<td>1.240</td>
<td>1.063</td>
<td>0.921</td>
<td>1.096</td>
<td>1.182</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0.683</td>
<td>0.992</td>
<td>1.240</td>
<td>0.963</td>
<td>0.921</td>
<td>1.096</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.683</td>
<td>0.992</td>
<td>1.240</td>
<td>1.031</td>
<td>0.921</td>
<td>1.096</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>0.683</td>
<td>0.992</td>
<td>1.240</td>
<td>0.963</td>
<td>0.921</td>
<td>1.096</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>0.683</td>
<td>0.992</td>
<td>1.689</td>
<td>1.031</td>
<td>0.846</td>
<td>1.122</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.448</td>
<td>0.992</td>
<td>1.689</td>
<td>1.031</td>
<td>0.846</td>
<td>1.122</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Costs and Cycle Energies:
- \( r_c \) $/MWH
- \( E_{rc} \) GWH
year horizon. Though Conclusion I continues to be valid with few violations, evidence supporting Conclusion II is non-existent. However, each inconsistency in these incremental costs as cycles begin and end, can be translated directly into the optimal loading order. During reactor-cycle E-3 (with \( \lambda^*_{E,3} = 1.689 \$/MWH \)), Reactor E is loaded only after all other nuclear units (with \( \lambda^*_{rc} = 1.240 \$/MWH \)) are fully loaded. Since for economic reasons E-3 is always last, it generates \( E^\text{min}_{E,3,t} \) during each included period of cycle 3 and, hence, \( E^*_{E,3} = E^\text{min}_{E,3} \). As Figure 1.15 illustrates, this lower limit on cycle energy prevents E-3 from reaching the cost parity of Conclusion I. (If \( E_{E,3} \) was less than \( E^\text{min}_{E,2} \), obviously uneconomic fossil energy costing over 2 \$/MWH would be substituted for its 1.7 \$/MWH energy.)

Reactor-cycle F-1 of Figure 1.14 has the opposite problem. With the initial core configuration assumed fixed, \( \lambda^*_{F,1} \) is a (cheap) short-range incremental cost. (Cycle burn-up is the only design variable.) Thus, Reactor F is always loaded first, generating \( E^\text{max}_{F,1} \) for the cycle. In an analogous manner, this upper limit on cycle energy can also prevent incremental cost parity.

The other \( \lambda^*_{rc} \) inconsistencies of Figures 1.13 and 1.14 are merely more complicated versions of these two simple cases--reactor-cycles E-3 and F-1. In each instance, the optimal economic period loading order is easily deduced: cheapest first.
Figure 1.15

Lower Limit on Cycle Energy Preventing Incremental Cost Parity

\[ \lambda_{E,3} \text{ CYCLE ENERGY (10}^3 \text{ GWH)} \]

\[ \lambda_{E,3} \text{ INCREMENTAL COST ($/MWH)} \]

\[ \lambda_{E,3} = 1.689 \$/MWH \]

1.240 $/MWH OF OTHER REACTORS

INCREMENTAL COST PARITY AT 1.240 $/MWH

REFUELING DATES ARE FIXED FOR A PARTICULAR STRATEGY, BUT CYCLE ENERGY IS NOT.
Comparing all reactor-cycles of Figures 1.13 and 1.14, $\lambda_{rc}^*$ is seldom over 1.41 $/\text{MWH}$. As Figure 1.2 pointed out, base-loading of a utility system's nuclear reactors may be impossible because the utility's minimum load is too low. However, since $\lambda_N$ is always much less than $\lambda_F$ (>2.0 $/\text{MWH}$), two possibilities exist for economically utilizing the excess nuclear capacity during the low load periods. One alternative is to sell excess nuclear capacity (i.e., energy) to neighboring utilities at a price greater than its incremental cost. Incorporation of such nuclear economy interchange sales into the SIM and SOM is desirable since this may well become a common utility practice.

The second option is to use the excess capacity on the utility's own system by operating a pumped-hydro station. By pumping during low load hours, $\lambda_P = \lambda_N \leq 1.4$ $/\text{MWH}$. Using the stored energy for peak-shaving high cost fossil the next day, $\lambda_G = \lambda_F > 4$ $/\text{MWH}$. Even if overall pumped-hydro efficiency is only 67%, total operating revenue requirements are reduced roughly 2 $/\text{MWH}$ (i.e., 50% of $\lambda_P$) for each fossil MWH displaced. Since such a station is also comparatively cheap to install (100-200 $/\text{kwe}$), a pumped-hydro station on the grid of a heavily nuclear utility produces startling economies (21, 35). "From a utility's viewpoint, pumped storage is a natural fit with large base-load plants. It can take on load instantly, it uses off-peak power to replenish its resources, and its reliability is second to none (5)."
As pumped-hydro stations become more numerous [-4400 MW installed versus over 8000 MW under construction in entire United States at end of 1972 (5)], the appropriate planning tools must be developed. Thus, it is highly recommended that pumped-hydro units (and hydro units, as well) be incorporated into the SIM.

Underlying the above discussion of incremental costs is the source of those costs--the CORSOM, or specifically, the QKCORE in-core simulator developed merely to test the SOM. By forgoing reload optimization, QKCORE is unable to see some obvious means of saving money. For instance, reactor-cycle E-3 of Figure 1.14 has a very high incremental cost due to energy production requiring 4% enriched reload fuel. Yet, the previous cycle loaded the minimum enrichment allowed (1.5%). If QKCORE allowed early shutdown (reactivity > 0) and optimized the enrichments alone, it might well have loaded 2.5% fuel in E-2, burned only part of the way down and then loaded 3.0% fuel for a complete burn. Indeed, a full-scale CORSOM would be able to optimize reload batch size, as well. What would be the optimum incremental costs for such modes of operation? Obviously, the incorporation of more versatile CORSOM's is a prerequisite to completing a fully operational nuclear power management model.
1.8.3 **Computational Requirements**

The computational requirements of SYSINT are detailed in Section 1.6.2 while SYSOPT details can be found in Section 1.7.2. However, Table 1.4 presents a summary of computer usage for Strategy 2.

1.8.4 **Evaluation of Competing Strategies**

Having discussed the properties of a single optimized strategy, it now becomes appropriate to discuss the broader question of strategy versus strategy comparison. In particular, given the same set of input data (i.e., forecasts), which of the individually optimized strategies represents the optimum plan for operating the utility system? How sensitive is this choice to various parameters in the input? To answer these questions, the results for the three Strategies over a four year horizon are presented in Table 1.5.

Recall that S-1 is an annual refueling strategy, S-2 a gradual shift to longer cycles and S-3 an immediate shift to longer cycles.

Of prime importance in correlating the results, is the refueling downtime of each strategy. Naturally, the more rapid the shift to longer cycle lengths, the fewer refuelings that must be scheduled.

With less nuclear downtime, the nuclear energy production increases and fossil energy production decreases by approximately the same amount. Also, startup-shutdown cost is decreased as the fossil units move farther away from nightly
Table 1.4

**Computational Requirements for Strategy 2**

*(Based on IBM 370 model 155 computer operating in MVT environment)*

<table>
<thead>
<tr>
<th>Program</th>
<th>Total Core Storage (Bytes)</th>
<th>CPU Time</th>
<th>Input/Output Time</th>
<th>Time Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>SYSINT</td>
<td>134 K</td>
<td>2.2</td>
<td>0.5</td>
<td>Sec/period</td>
</tr>
<tr>
<td>SYSOPT</td>
<td>246 K with overlay</td>
<td>9</td>
<td>7</td>
<td>Sec/inner iteration</td>
</tr>
<tr>
<td>QKCORE</td>
<td>371 K without overlay</td>
<td>13</td>
<td>&lt;1</td>
<td>Sec/inner iteration</td>
</tr>
</tbody>
</table>
TABLE 1.5  
REVENUE REQUIREMENTS AND UNDISCOUNTED ENERGY OVER FOUR YEARS  
(48 Month Horizon, 7% P.V. Rate, Reference Nuclear Unit Costs,  
No Shape Constraints)

<table>
<thead>
<tr>
<th>Strategy</th>
<th>S-1</th>
<th>S-2</th>
<th>S-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downtime to horizon (reactor-months)</td>
<td>38</td>
<td>33</td>
<td>31</td>
</tr>
<tr>
<td>Average cycle length (months)</td>
<td>12</td>
<td>14.5</td>
<td>15.2</td>
</tr>
<tr>
<td>System nuclear capacity factor</td>
<td>0.638</td>
<td>0.647</td>
<td>0.651</td>
</tr>
</tbody>
</table>

\[
10^6 \text{\$} \\
(10^6 \text{ MWH})
\]

<table>
<thead>
<tr>
<th></th>
<th>S-1</th>
<th>S-2</th>
<th>S-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuel</td>
<td>184.223</td>
<td>176.348</td>
<td>173.250</td>
</tr>
<tr>
<td></td>
<td>(51.703)</td>
<td>(50.061)</td>
<td>(49.390)</td>
</tr>
<tr>
<td>Startup-shutdown cost</td>
<td>1.497</td>
<td>1.281</td>
<td>1.227</td>
</tr>
<tr>
<td>Emergency purchases</td>
<td>0.464</td>
<td>0.317</td>
<td>0.265</td>
</tr>
<tr>
<td></td>
<td>(0.053)</td>
<td>(0.036)</td>
<td>(0.030)</td>
</tr>
<tr>
<td>Nonnuclear production</td>
<td>186.184</td>
<td>177.946</td>
<td>174.742</td>
</tr>
<tr>
<td></td>
<td>(51.756)</td>
<td>(50.097)</td>
<td>(49.420)</td>
</tr>
<tr>
<td>Nuclear fuel</td>
<td>198.267</td>
<td>197.189</td>
<td>199.821</td>
</tr>
<tr>
<td></td>
<td>(118.376)</td>
<td>(120.035)</td>
<td>(120.712)</td>
</tr>
<tr>
<td>System production</td>
<td>384.451</td>
<td>375.135</td>
<td>374.563</td>
</tr>
<tr>
<td></td>
<td>(170.132)</td>
<td>(170.132)</td>
<td>(170.132)</td>
</tr>
<tr>
<td>Fixed firm purchase</td>
<td>95.166</td>
<td>95.166</td>
<td>95.166</td>
</tr>
<tr>
<td></td>
<td>(54.312)</td>
<td>(54.312)</td>
<td>(54.312)</td>
</tr>
<tr>
<td>Penalty for short-notice enrichment changes</td>
<td></td>
<td></td>
<td>2.000</td>
</tr>
<tr>
<td>System Total</td>
<td>479.617</td>
<td>470.301</td>
<td>471.729</td>
</tr>
<tr>
<td></td>
<td>(224.444)</td>
<td>(224.444)</td>
<td>(224.444)</td>
</tr>
</tbody>
</table>
shutdown. Fewer emergency energy purchases are required due to increased on-line resource margins.

All three components of non-nuclear production cost thus favor reducing downtime. (By looking at the differences in non-nuclear production cost, average long-term levelized replacement energy costs of 5.2-5.7 $/MWH can be calculated.)

As mentioned above, each succeeding strategy is able to increase production because of less refueling downtime. However, the cost of this energy does not increase proportionally. In fact, compared to S-1, S-2 generates more nuclear energy for less money! To explain this anomaly, consider the following:

(1) Less downtime means fewer reloads must be purchased.

(2) Increased average cycle length, however, means increased cycle energy and reload enrichment.

(3) Even with increased batch enrichment cost, the savings due to foregone reloads and the increased energy for amortizing fixed costs, etc., result in a 1.9% decrease in levelized nuclear fuel costs over the four year horizon.

(4) Due to fixed initial conditions and only gradual shift to longer cycles, S-1 and S-2 are very similar in energy production during the first year. At the end of four years, energy production by S-2 is only 1.4% higher. (For longer horizons, the first year
matters less and energy production differences are greater."

(5) Finally, since the levelized nuclear fuel cost decreases percentagewise more than energy production increases, the net result is more nuclear energy for less money.

Turning to S-3, the immediate shift to longer cycles results not only in increased energy production, but also in increased levelized fuel cost. The result is a return to normalcy--more nuclear energy costs more.

Looking then at system production cost, S-3 saves $570,000 over S-2 and roughly ten million dollars over S-1. This, of course, is not enough to absorb S-3's assumed additional two million dollars in penalties for the two short notice enrichment changes required for the immediate shift to longer cycles. Thus, among the three strategies, S-2 has minimum total system cost.

During the first four years, then, S-2's gradual shift to longer cycles saves 9.3 million dollars compared to the annual cycles of S-1. Such a savings clearly justifies a few hundred thousand dollars in overhead necessary to implement the engineering design changes in the reload fuel specifications.

However, S-2 and S-3 are roughly competitive depending on the magnitude of the enrichment change penalty. Without the penalty S-3 is favored by roughly $600,000. (Of this
$600,000, roughly $95,000 could also be saved by S-2 were it allowed to freely change initial enrichment for two of the reactors.) But after the 2 million dollar penalty, S-3 is 1.4 million dollars more costly.

1.9 Summary

This work presents a multi-reactor, multi-year fuel management model consisting of four sub-models (RAMM, SIM, SOM and CORSOM). The SIM and SOM sub-models have been discussed in some detail. Numerical results were presented as an example of the model's ultimate versatility. Some work remains to be done before the completely computerized nuclear power management multi-year model is ready for implementation on nuclear utility systems. The most severe deficiency is not in either the SIM (SYSINT) or the SOM (SYSOPT), but is due to the large computational requirements of current PWR CORSOM's (estimated at several hours for optimizing a single refueling and maintenance for the entire utility system). In addition, CORSOM's for the other types of reactors are also needed. Acceptable RAMM's already exist [e.g.,(20)] and merely require proper interfacing.

As for the major required improvements in SYSINT and SYSOPT, there are two: (1) addition of hydro and pumped-hydro unit types (likewise, permitting initial cycles of nuclear units to be treated as a scarce-resource initial condition) and (2) on-line sensitivity analysis of the
effect on total operating revenue requirement of various forecasting errors, such as incorrect customer load demands or unit performance probabilities.
2.1 Characteristics of a Utility

An electric utility, like any other business enterprise, exists because its product fulfills an established need. The utility generates electricity to supply the requirements, or load, demanded by the customers in its geographical service region. The utility's objective is to do so at minimum total cost.

These three characteristics (load demand, power supply and utility objective) must be fully understood before system optimization techniques can be successfully applied to utility management problems.

2.1.1 The Demand: Customer Loads

The load supplied by a utility at any one instant in time is the sum of the individual loads demanded by thousands of customers. These loads range from a residential customer's 40-watt light bulb to a heavy industrial customer's 100 MW's of factory equipment. The statistical nature of the sum of hundreds of thousands of residential customers, thousands of commercial customers and scores of industrial customers makes minute-by-minute load patterns far too cumbersome for even daily management planning work. The typical unit of analysis is the average load during the hour. These hourly loads follow definite daily and weekly patterns for each utility (see Figure 2.1). Minimum loads range from 35% to 60% of peak demand depending on the utility's mix of large round-the-clock heavy industrial customers and small cyclical loads due to residential
Figure 2.1

Typical Weekly Load Pattern for an Electric Utility

Maximum Load = 7050 MW

Average Load = 5190.5 MW
Total Energy = 872,004 MWh

Minimum Load = 3120 MW

Load (10^3 MW)
and commercial customers. Even for the same utility, seasonal variations and annual load growth affect these patterns.

For daily (or even annual) models, chronological hourly load detail may be appropriate. However, multi-year and long-range models cannot afford to look at each of the 8760 hours in each year. For these models, the load-duration curve is more appropriate. Figure 2.2 presents the load-duration curve for the data of Figure 2.1. The 168 hours in the week are merely rearranged in order of decreasing load demand. Thus, the peak demand occurs during the first hour of the new time scale and the minimum load occurs during the last hour. The interpretation of the new time scale is the number of hours the load was greater than or equal to a specified power level—in short, the load's duration.

The rearrangement of loads results in the complete loss of chronological information, but preserves the more important property that the integral under the curve is the total energy demanded during the week.

Realizing hourly loads are actually averages of a rapidly changing but continuous function, such histograms are usually drawn as smooth curves. In addition, two other changes are made to the load representation throughout the work reported here. First, the axes are reversed so that the power level $P$ is the abscissa and duration $d$ the ordinate (see Figure 2.3). This facilitates mathematical treatment of power level as the independent variable and duration as the dependent variable. The second alteration involves normalizing the duration scale by the total length of the time period $T'$. The new zero-to-one ordinate scale can be interpreted as not only the fractional duration $F$ but, more importantly, as the probability that the load will be greater than or equal to the specified power level at a random instant of time. From Figure 2.3, the load
Figure 2.2

Load-Duration Curve (Standard Format) for the Typical Week

Maximum Load = 7050 MW

Average Load = 5190.5 MW
Total Energy = 872,004 MWh

Minimum Load = 3120 MW

P, Load (10^3 MW)

D, Duration (Hours)
Figure 2.3

Load-Duration Curve (Altered Format) for the Typical Week

- **Knee** of Load-Duration Curve

- Minimum Load = 3120 MW

- Average Load = 5190.5 MW
- Total Energy = 872,004 MWh

- Maximum Load = 7050 MW
was always (100% of the time) greater than or equal to the minimum load of 3120 MW, but never (0% of the time) greater than the peak of 7050 MW.

Neither of these changes alters the basic property that, in the correct units, the integral under the curve is the total energy demanded during the time period,

\[
D_T = \int_0^\infty T \cdot \frac{d}{dP} = T' \int_0^\infty \left(\frac{d}{T'}\right) dP = T' \int_0^\infty F dP
\]  

(2.1)

2.1.2 The Supply: Generating Equipment

2.1.2.1 Types

In providing installed capacity to meet the customer loads, a utility relies on up to five different types of generating equipment:

1. Nuclear units: very large capacity units generating electricity via the heat released by a sustained nuclear chain reaction contained within the reactor's core. If the core coolant exits as a gas or vapor (as in a BWR), it may be expanded directly in turbine-generators. Otherwise, the heat may be first transferred in boilers to produce expandable steam (as with a PWR).

2. Fossil steam units: typically large capacity coal, oil and/or gas-fired boilers producing high temperature-high pressure steam that is expanded in turbine-generators.

3. Fast-start peaking units: small fossil-fueled jet engine, gas turbine or diesel-driven generators.

4. Hydro units: typically medium capacity hydroelectric turbines housed in man-made dams. These dams create the necessary water height differential, or head, by trapping a river's inflows in the reservoir behind the dam.
(5) Pumped-hydro units: similar to hydro except that the dual-purpose turbine may also operate as a pump, transferring water from the foot of the dam to the reservoir. Like a storage battery, excess energy is temporarily stored in another form (water at a height) for later retrieval by reversing the process.

2.1.2.2 Data Required On Each Unit

Regardless of the type of unit, certain key information is required by the system planner on each and every unit of the system:

1. minimum and maximum power level,
2. fuel consumption vs. power level,
3. fuel cost,
4. fuel inventory,
5. transmission losses,
6. startup-shutdown data,
7. maintenance requirements and
8. reliability data.

Table 2.1 presents a general summary of these characteristics for each unit type, including capital cost estimates.

The minimum and maximum power levels indicate the lower and upper bounds, respectively, for continuous plant operation. Below the minimum (typically 10 to 50 percent of the maximum), engineering problems, such as boiler flame instability for fossil units, preclude reliable and sustained operation. Similarly, stressing the unit above its maximum power level would be unwise.

1 Throughout this work, all power levels are in units of net MWe delivered to the transmission system busbar. That is, plant auxiliary power requirements (~5%) have already been subtracted from gross generator output, but transmission losses have not been accounted for.
TABLE 2.1
Characteristics of Types of Electric Generating Units

<table>
<thead>
<tr>
<th>System Use</th>
<th>Dimension</th>
<th>Nuclear Steam (LWR)</th>
<th>Fossil Steam</th>
<th>Fast-Start Peaking</th>
<th>Hydro</th>
<th>Pumped-Hydro</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Base-Load</td>
<td>Base-Load and Cyclical</td>
<td>Peaking</td>
<td>Inventory Dependent</td>
<td>Peaking</td>
</tr>
<tr>
<td>Capacity Fact.</td>
<td>Percent</td>
<td>60-90</td>
<td>30-90</td>
<td>Up to 20</td>
<td>Up to 100</td>
<td>Up to 50</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>$/kwe</td>
<td>300-450</td>
<td>250-400</td>
<td>100-150</td>
<td>300-500</td>
<td>100-200</td>
</tr>
<tr>
<td>Unit Capacity</td>
<td>MW</td>
<td>500-1200</td>
<td>200-1200</td>
<td>10-50</td>
<td>10-600</td>
<td>50-400</td>
</tr>
<tr>
<td>Min. Power</td>
<td>% Cap.</td>
<td>10-40</td>
<td>10-50</td>
<td>75-90</td>
<td>0-10</td>
<td>25-40</td>
</tr>
<tr>
<td>Avg. Ht. Rate</td>
<td>MBTU/MWH</td>
<td>10.5-11</td>
<td>8.5-14</td>
<td>12-17</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Conversion Eff.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Cost</td>
<td>¢/MBTU</td>
<td>16-20</td>
<td>35-80 (Coal)</td>
<td>50-100</td>
<td>0</td>
<td>Cost of pumping power</td>
</tr>
<tr>
<td>Energy Cost</td>
<td>$/MWH</td>
<td>1.7-2.2</td>
<td>3.0-8.4</td>
<td>6.5-20</td>
<td>0</td>
<td>~1.5 X pumping power</td>
</tr>
<tr>
<td>Comments on Fuel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inventory</td>
<td></td>
<td>Depends on fuel cycle</td>
<td>Approx. const. at 100 days supply</td>
<td>4-8 hours (Oil)</td>
<td>Depends on season</td>
<td>Depends on operating cycle</td>
</tr>
<tr>
<td>Trans. Losses</td>
<td>Percent</td>
<td>Up to 10</td>
<td>Up to 10</td>
<td>Up to 5</td>
<td>Up to 10</td>
<td>Up to 15</td>
</tr>
<tr>
<td>SU-SD Ht. Reqt.</td>
<td>MBTU/MW Cap.</td>
<td>3-6</td>
<td>3-8</td>
<td>0-2</td>
<td>~0</td>
<td>~0</td>
</tr>
<tr>
<td>Min. SD Time</td>
<td>Hours</td>
<td>&lt;2</td>
<td>2-10</td>
<td>&lt; 0.3</td>
<td>&lt; 0.5</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Maint. Reqt.</td>
<td>Week/Year</td>
<td>4-8 wk/refuel</td>
<td>3-5</td>
<td>1-4</td>
<td>1-2</td>
<td>1-2</td>
</tr>
<tr>
<td>Forced-Out Rate</td>
<td>Percent</td>
<td>Up to 15</td>
<td>Up to 20</td>
<td>Up to 40</td>
<td>Up to 5</td>
<td>Up to 10</td>
</tr>
<tr>
<td>Perf. Prob.</td>
<td>Percent</td>
<td>85-100</td>
<td>80-100</td>
<td>90-100</td>
<td>95-100</td>
<td>95-100</td>
</tr>
</tbody>
</table>
Fuel consumption data are important in characterizing the unit's thermal efficiency as a function of its power level. Figure 2.4 presents $H$ (heat input rate) versus $P$ (power level) at the valve points typical of a fossil generating unit. Defining $\bar{h}$ and $h_{inc}$ as the average and incremental heat rates, respectively,

$$\frac{H}{P} = \bar{h} = \frac{3.413}{\eta} \text{ Mega BTU/MWH} \quad (2.2)$$

$$\frac{dH}{dP} = h_{inc} = \frac{3.413}{\eta_{inc}} \text{ Mega BTU/MWH} \quad (2.3)$$

During fuel consumption tests, $H$ can only be measured to within a few percent (20). This uncertainty plus the complicated nature of the true $H$ curve (4, 52) make the actual derivative $dH/dP$ impossible to obtain. The result is that $\Delta H/\Delta P$ is usually substituted and treated as a constant for each capacity increment (i.e., between valve points). Figure 2.5 presents $\bar{h}$ and $h_{inc}$ for the data of Figure 2.4. With $h_{inc}$ interpreted as the additional heat input required to generate the next increment of electrical energy, $H(P > K_1)$ can be expressed mathematically as,

$$H(P) = H_1 + \int_{K_1}^{P} \frac{dH}{dP} \, dP = \bar{h}_1 K_1 + \int_{K_1}^{P} h_{inc} (P) \, dP \quad (2.4)$$

In terms of thermal energy, heat rate data can be treated as constant for years at a time. By then applying $\phi$ time-dependent thermal energy fuel cost, similarly shaped time-dependent incremental energy costs can be calculated,

$$\lambda(P, t) = h_{inc} (P) \phi(t) \quad \text{and} \quad \bar{e}_1 = \bar{h}_1 \phi(t) \quad (2.5)$$

In the same way that fuel cost has more meaning for a fossil plant than for a hydro unit (where the water is normally assumed to be free), fuel inventory information pertains specifically to the energy-limited type
Figure 2.4
Heat Input Rate versus Net Power Output Level for Typical Fossil Unit [After (37)]

Assuming ±4% error in H data (52)

- Fifth Valve (maximum load)
- Fourth Valve
- Third Valve
- Second Valve
- True Behavior
- Assumed Behavior
- Primary Valve Fully Open (minimum load)

\[ h_{inc} = \frac{\Delta H}{\Delta P} \]

\[ h = \frac{H}{P} \]

\[ K_1 = \text{minimum} \]

\[ \text{Maximum} = K_5 \]
Figure 2.5

Heat Rates versus Net Power Output Level for Typical Fossil Unit

NOTE: SUBSCRIPT DENOTES VALVE POINT NUMBER
of units—nuclear, hydro and pumped-hydro. Fossil fuel inventories are normally maintained at about a 100-day supply (20). Thus, deliveries and consumption can be treated under LIFO last-in, first-out accounting procedures while considering the fuel inventory as an additional initial fixed plant investment. On the other hand, the nature of the nuclear unit's fuel cycle (i.e., core reactivity requirements), the seasonal nature of a hydro unit's river inflows and the weekly pumping-generating cycles of a pumped-hydro unit create situations when there is not enough of the cheap resource to operate the unit at full power all the time. The fuel (or water) becomes a so-called "scarce resource." Generating decisions utilizing scarce resources require a separate method of analysis (see Sections 2.2.2 and 2.2.3).

Transmission losses from the generating unit to the load center must be accounted for. If the customer demands 10 MW, a unit 150 miles away may have to generate 11 MW. Though detailed load flow calculations are required for on-line dispatching (43), more approximate representations are suitable for planning scales on the order of months or years. One of the simplest assumptions is that each unit loses a characteristic percentage of its generation due to this resistance heating. The net MW output for each valve point can then be written down by this percentage so that, just as load demand is in units of MW at the load center, so is unit production. An even simpler assumption (and the one adopted throughout this work) is that transmission losses are negligible or, at least, invariant.

Included in startup-shutdown data are generally three pieces of information: (1) the net cost in time-dependent units of equivalent thermal energy input required for a combined startup-shutdown sequence (see Figure 2.6), (2) the minimum shutdown time (i.e., it is not practical to
### Startup-Shutdown Cost Data Sheet

#### Generating Station Data

<table>
<thead>
<tr>
<th>Shutdown, From</th>
<th>To</th>
<th>$ Per:</th>
<th>Dollars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignition Fuel, Gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ignition Fuel, Oil</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal Fuel, Gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal Fuel, Coal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additional Labor</td>
<td>1</td>
<td>Hours</td>
<td></td>
</tr>
<tr>
<td>Auxiliary Power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generation (Gross)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Idle Period, From</th>
<th>To</th>
<th>$ Per:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignition Fuel, Gas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ignition Fuel, Oil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal Fuel, Gas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal Fuel, Oil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auxiliary Power</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Startup to Normal Load Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>From</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Ignition Fuel, Gas</td>
</tr>
<tr>
<td>Ignition Fuel, Oil</td>
</tr>
<tr>
<td>Normal Fuel, Gas</td>
</tr>
<tr>
<td>Normal Fuel, Coal</td>
</tr>
<tr>
<td>Additional Labor</td>
</tr>
<tr>
<td>Auxiliary Power</td>
</tr>
<tr>
<td>Generation (Gross)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grand Total:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub Total:</td>
</tr>
</tbody>
</table>

**Equivalent Normal Fuel** 820 Mega BTU * $.50 = 410 10

**One Hour Normal Operation**

<table>
<thead>
<tr>
<th>Normal Fuel</th>
<th>Auxiliary Power</th>
<th>Generation (Gross)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Gross</th>
<th>Net</th>
</tr>
</thead>
</table>

Signed: T. A. Edison  
Date: 5/3/73
shut down a fossil unit and then have it back on-line within an hour or so even if it were economically attractive), and (3) maximum rate of change of power due to engineering limitations. For a model simulating operation on the order of years, only the startup-shutdown cost is required. For models dealing with day-to-day operating decisions (and restrictions), all three must be included.

Preventive maintenance is performed to keep the units in good operating order. Typically, each unit type has a periodic maintenance requirement, such as two weeks per year. As for scheduling this maintenance, most utilities have an annual peak demand period (frequently the summer months) when scheduled maintenance is prohibited to provide the maximum possible system resources (i.e., wholly-owned generating capacity plus the committed capacity of neighboring utilities) to meet the peak. On a calendar, these taboo periods act as partitions between scheduling windows. It is during these windows that all of the system's required maintenance must be scheduled.

Reliability data account for unscheduled maintenance downtime due to a unit being forced out of service by operating problems, a "forced-outage." Normally quoted is the forced-outage rate FOR defined by the Edison Electric Institute (7) (see Figure 2.7) as

\[
FOR = \frac{\text{FOH}}{\text{FOH} + \text{SH}}
\]  

(Instances of merely derating the unit capability to less than full power due to equipment problems, "forced-deratings," have been ignored.) Currently, the utility industry is continuing (2) to discuss the proper measurement of unit reliability. For this reason, the following detailed discussion is presented.
Figure 2.7
Edison Electric Institute Definitions Related to Equipment Availability (Assuming No Forced-Deratings)

- AVAILABLE
- SERVICE
- SH
- REF: AFTER (2) AND (Z)
- AH
- RESERVE SHUTDOWN
- RSH
- FORCED-OUTAGE (SERVICE OTHERWISE)
- FOSH
- TOTAL PERIOD HOURS
- FORCED-OUTAGE (RESERVE OTHERWISE)
- FORH
- "H" = HOURS EEI STD.
- SUGGESTED HERE
- SCHEDULED OUTAGE
- MAINT. (REPAIR) OUTAGE
- MOH
- PLANNED (PREVENTIVE) MAINT. OUTAGE
- SOH
- POH

QEEI STD.
QD SUGGESTED HERE
Defining the "importance" $f$ as the fraction of forced-outage hours occurring when service was desired \(^{(2)}\), the suggested breakdown of FOH in Figure 2.7 becomes

\[
FOSH = f \cdot FOH \tag{2.7}
\]

\[
FORH = (1-f) \cdot FOH \tag{2.8}
\]

These additions are required because FOR is not always an accurate indication of how often the unit did not perform when it was called upon. A much better indication of forced-outage effects is $q$, the nonperformance probability defined as,

\[
q = \frac{FOSH}{FOSH + SH} \tag{2.9}
\]

Thus the probability that the unit will perform service when called upon, $p$, can be defined as

\[
p = 1 - q \tag{2.10}
\]

Returning to Equation (2.9) and utilizing Equation (2.7),

\[
q = \frac{f \cdot FOH}{FOSH + SH} \tag{2.11}
\]

From Equation (2.6),

\[
FOH = SH\left(\frac{FOR}{1-FOR}\right) \tag{2.12}
\]

Therefore,

\[
q = \frac{SH\left(\frac{FOR}{1-FOR}\right)f}{SH\left(\frac{FOR}{1-FOR}\right)f + SH} \tag{2.13}
\]

Rearrangement and cancellation lead to the following result,

\[
q = \frac{f \cdot FOR}{1 - FOR(1-f)} \tag{2.14}
\]
Figure 2.8 plots the nonperformance probability as a function of the forced-outage rate and the importance. As \( f \) approaches 1, \( q \) approaches \( \text{FOR} \) as would be expected for base-load units which are operated whenever possible. On the other hand, forced-outage rate statistics of around 20\% to 40\% for peaking units make these units appear very unreliable. Considering their low utilizations of around 10\%, \( \text{FOR} \) converts into a respectable 2.5\% to 6\% nonperformance probability.

2.1.2.3 Five-Unit Reference Utility System

A small Reference Utility System consisting of five units will be used throughout Chapters 2 and 3 for presenting numerical examples designed to assist the reader in understanding the procedures developed here. Quoting Wagner (54), "the manager who resolutely avoids familiarizing himself with the basic mechanism [underlying] his ... application is flirting with trouble. If he really wants to maintain control, he must nurture his insight to the approach."

The pertinent unit data are presented in Table 2.2. The normalized load-duration curve of Figure 2.9 represents the typical month's (730 hour) customer demands. A convenient step size of 100 MW is used for all calculations. A summary of all six examples is presented in Appendix B.

As a final note, a much larger hypothetical utility system consisting of 46 generating units will be used for the nuclear power management model evaluation in Chapter 5. (See Section 5.3.)
Figure 2.8

Non-Performance Probability as a Function of Forced-Outage Rate and Importance

\[ q = \frac{f \cdot \text{FOR}}{1 - \text{FOR}(1-f)} \]

FOR, FORCED-OUTAGE RATE (PERCENT)

q, NON-PERFORMANCE PROBABILITY (PERCENT)
TABLE 2.2
Unit Characteristics for Reference Utility System

Total Capacity = 2000 MW

<table>
<thead>
<tr>
<th>Unit Name</th>
<th>Type</th>
<th>Rated Cap.</th>
<th>Perf.</th>
<th>Fuel Cost</th>
<th>SUSD. Heat</th>
<th>Valve Point Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(K_r) MW</td>
<td>(P_r) %</td>
<td>(\phi_r)</td>
<td>(Q_r) MBTU</td>
<td>(K_{r1}) MW</td>
</tr>
<tr>
<td>I</td>
<td>P^2</td>
<td>100</td>
<td>95</td>
<td>90</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>II</td>
<td>F</td>
<td>200</td>
<td>95</td>
<td>50</td>
<td>800</td>
<td>100</td>
</tr>
<tr>
<td>III</td>
<td>N</td>
<td>300</td>
<td>90</td>
<td>19</td>
<td>1200</td>
<td>100</td>
</tr>
<tr>
<td>IV</td>
<td>F</td>
<td>600</td>
<td>90</td>
<td>40</td>
<td>3600</td>
<td>200</td>
</tr>
<tr>
<td>V</td>
<td>N</td>
<td>800</td>
<td>85</td>
<td>18</td>
<td>2400</td>
<td>300</td>
</tr>
</tbody>
</table>

1 Equivalent startup-shutdown heat requirement

2 F = Fossil, N = Nuclear, P = Peaking

3 MBTU = Mega BTU
Figure 2.9

Normalized Customer Load-Duration Curve for 730 Hour Month on Reference Utility System

F, Probability (P ≥)

P, Load (MW)

MINIMUM DEMAND 800 MW

F, CUSTOMER LOAD-DURATION CURVE

DT = 949 MWH

0.80 AT 1200 MW

0.20 AT 1400 MW

PEAK DEMAND 1800 MW

INSTALLED CAPACITY 2000 MW
2.1.3 The Objective: Supply All Demands at Minimum Cost

The electric power supply industry is often chosen as the textbook example of pure monopoly. In fact, electric power is a "natural monopoly" because economies-of-scale with regard to investment in generating and transmission equipment make competition impossible (56). "Recognizing the advantages...of avoiding wasteful duplication and competition, the public [the utility's customers]...grants a utility an exclusive franchise for its particular service in a given geographical region [24]."

As a means of controlling the utility investor's rate-of-return, the Federal Power Commission and state public utilities commissions retain the right to oversee the utility's actions vis-à-vis the public interest. In particular, the local commissions must approve all changes in the electricity rate structure (i.e., prices charged to the utility's customers).

With the rates per unit electricity fixed externally by the regulatory commissions and the total amount of electricity determined externally by the customers' demands, the total revenue received by the utility is also fixed (albeit, in a probabilistic sense). By minimizing the revenue required to recover the cost of supplying that electricity, the utility maximizes total profit. Therefore, the utility objective function is the minimizing of the present value of all future required revenue, i.e., the revenue requirement. (Present valuing accounts for the time value of money.) This sum represents that amount of money which, if received immediately and invested in the company, would just suffice to pay all expenses, as well as permitting a fair return to investors.2 By including investors' permitted return as another cost component, "revenue requirement" and "total cost" become synonymous. The utility decision-maker is thus responsible for supplying all customer load demands in a reliable manner at minimum total cost.

2More precisely (55),
"The revenue requirement is that sum of money, which if received as revenue by an investor-owned electric utility at the beginning of the planning horizon and invested in the enterprise, will defray all subsequent fuel cycle costs, the return allowed by regulatory agencies on that portion of the original investment remaining unexpended at any time, and defray all associated income taxes."
In accounting for all the costs relative to utility operation, revenue is required for the following items:

1. investment in equipment and facilities,
2. fuel consumption,
3. electricity purchases from (less sales to) neighboring utilities,
4. overhead expenses,
5. labor and supplies,
6. maintenance expenses,
7. taxes and
8. carrying charges on all of the above.

When considering different operating strategies over a multi-year time horizon (on the order of 5 years), many of the above components are essentially fixed. The long lead times required to effect changes in current equipment installation plans remove item (1) from the multi-year decision-maker's control. On the other hand, total strategy overhead (item 4), labor and supplies (item 5) and maintenance (item 6) are largely invariant though the timing of the latter may be slightly altered by the multi-year strategist.

The multi-year objective function may, therefore, be reduced to the operating costs directly related to supplying customer loads--fuel consumption (item 2) and electricity purchases (item 3) along with the associated taxes (item 7) and carrying charges (item 8).

Adopting the notation that RR(X) is the total revenue requirement related to direct expenditure X,
\[ RR(X) = \text{Present (Expenditure X) Value} + \text{Present (Taxes associated with X) Value} + \text{Present (Carrying charges associated with X) Value} \] (2.15)

Fuel consumption expenditures can be further broken down into:

(1) \( X_F \), fossil fuel related directly to production,
(2) \( X_N \), nuclear fuel related directly to production, and
(3) \( X_S \), fuel related to startup-shutdown heat requirements.

Expenditures for electricity purchases from other utilities \( X_U \) represents both emergency purchases and economy purchases. (Economy purchases are not considered further in this work.)

The standard procedure in performing multi-year optimization is to subdivide the horizon into \( Z \) smaller time periods. In each time period \( p \), expenditures are estimated in undiscounted dollars. Period expenditures are then present-valued at \( x \) per year from their mean time \( \bar{t}_p \) back to time zero. As Section 2.3 will point out, the addition of nuclear units may prevent immediate evaluation of \( X_N \). [In fact, \( RR(X_N) \) or \( RR_N \) is determined directly only after all periods have been simulated.]

The equivalent multi-year objective function \( ORR \), the operating revenue requirement, can then be expressed as

\[ ORR = RR_F + RR_N + RR_S + RR_U \] (2.16)

or, in terms of the nonnuclear period expenditures,

\[ ORR = \sum_{p=1}^{Z} X_F \frac{1}{(1+x)^{\bar{t}_p}} + RR_N + \sum_{p=1}^{Z} X_S \frac{1}{(1+x)^{\bar{t}_p}} + \sum_{p=1}^{Z} X_U \frac{1}{(1+x)^{\bar{t}_p}} \] (2.17)
2.2 Production Scheduling

Given the predicted customer loads and generating equipment, how are operating expenditures on the Reference System estimated? Much work has been done on modelling utility production scheduling (9, 18, 30, 43, 48, 52, 53). A relatively new technique, the Booth-Baleriaux probabilistic system model (10,19) is rapidly gaining acceptance among utility system planners. The following sections describe qualitatively how the model schedules each type of unit. A quantitative description of the model has been postponed until Chapter 3.

2.2.1 Fossil, Peaking and Nuclear Units

As Section 2.4 will point out, the key element in any utility system optimization is incremental cost. Thus, the first step in any production scheduling technique is surveying the incremental costs of the available units. Using the rth unit and ith increment notation, Equation (2.5) becomes

\[ e_{rl} = \phi_r h_{rl} \quad \text{and} \quad \lambda_{ri} = \phi_r h_{inc_{ri}} \quad i > 1 \]  

(2.18)

Figure 2.10 presents the resulting incremental costs for the Reference System of Section 2.1.2.3. Utilizing these, the order in which the plant increments are started up and loaded (i.e., the startup and loading order) can be established. If all units but Unit I are assumed to be already running at their minimum loads (700 MW in toto), the question is "Which increment should then be loaded when the 701st MW is demanded?" The cheapest unused increment (1.71 \$/MWH per Figure 2.10) is that of Unit V. Thus, it is loaded until total demand reaches 1200 MW. Now Unit III's 1.90 \$/MWH increment should be loaded for the next 200 MW.
Figure 2.10

Incremental Costs for Reference Utility System (See Table 2.2)

- BASE-LOAD INCREMENTS IN EXAMPLE I

- AVERAGE COST FOR FIRST INCREMENT

- INCREMENTAL COST FOR SECOND INCREMENT

- POWER LEVEL (MW)

- INCREMENTAL COST ($/MMBtu)
This procedure of loading in order of increasing incremental cost results in the loading order and system incremental cost curve shown in Figure 2.11. Overlaying this loading order on the customer loads of Figure 2.9 yields the production schedule shown in Figure 2.12. Temporarily assuming all units are always operable (i.e., no forced-outages), energy production by each unit increment \( E_{ri} \) equals the total period length \( T' \) (the normalizing factor) times the area \( A_{ri} \) under that increment's section of the normalized customer load-duration curve,

\[
E_{ri} = T' A_{ri} = T' \int_{P_C}^{P^*} \Delta P_{ri} F(P) \, dP
\]  

(2.19)

and total unit energy production \( E_r \) is given by

\[
E_r = \sum E_{ri}
\]  

(2.20)

At an average incremental cost of \( \lambda_{ri} \), the cost of each energy increment is

\[
X_{ri} = \bar{a}_{ri} E_{ri} \quad \text{and} \quad X_r = \lambda_{ri} E_r \quad i > 1
\]  

(2.21)

and hence,

\[
X_r = \sum X_{ri}
\]  

(2.22)

Table 2.3 summarizes each unit's energy and cost totals for Example 1. (Startup-shutdown costs are ignored throughout this chapter.)

The above description is typical of older, deterministic utility models since all units were assumed always operable with no stochastic forced-outages. Example 2 (see Figure 2.13) portrays the more realistic case where each unit is assumed to have a fixed percentage of random downtime.
Figure 2.12

Production Scheduling for Example 1 (No Forced-Outages)

The diagram illustrates the production scheduling for an example with no forced outages. It shows the load-duration curve and the probability of load exceedance at various load levels. The installed capacity ($K_T$) is indicated at the right side of the diagram, and the load levels are marked with specific GWh values.
TABLE 2.3
Example 1 on Reference Utility System:
"Deterministic Model (No Forced-Outages)"
(See Appendix C for further details.)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Increment</th>
<th>Position in Loading Order</th>
<th>Increment Energy E&lt;sub&gt;ri&lt;/sub&gt; (GWH)</th>
<th>Increment Cost X&lt;sub&gt;ri&lt;/sub&gt; (10&lt;sup&gt;3&lt;/sup&gt; $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>9 (last)</td>
<td>- 0 -</td>
<td>- 0 -</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>4</td>
<td>73.00</td>
<td>401.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
<td>- 0 -</td>
<td>- 0 -</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>1</td>
<td>2</td>
<td>73.00</td>
<td>166.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6</td>
<td>73.00</td>
<td>138.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>1</td>
<td>3</td>
<td>146.00</td>
<td>572.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7</td>
<td>29.20</td>
<td>97.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>1</td>
<td>1 (first)</td>
<td>219.00</td>
<td>492.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5</td>
<td>335.80</td>
<td>574.2</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Utility Production</td>
<td></td>
<td></td>
<td>949.00</td>
<td>2442.9</td>
</tr>
<tr>
<td>Emergency Purchases (at 10$/MWH)</td>
<td></td>
<td></td>
<td>- 0 -</td>
<td>- 0 -</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>949.00</td>
<td>2442.9</td>
</tr>
</tbody>
</table>

Loss-of-Load Probability, LOLP = 0%
Figure 2.13

Production Scheduling for Example 2 (Deterministic Scheduling Using Reduced Rated Capacities)

F, PROBABILITY (P ≥)
0.00 0.25 0.50 0.75 1.00

P, LOAD (MW)
0 250 500 750 1000 1250 1500 1750 2000

Y-1 III-1 IV-1 II-1 V-2 III-2 IV-2

F CUSTOMER LOAD-DURATION CURVE

LOLP = 0.0125
D_L = 0.11 GWH

5.81 GWH II-1
2.51 GWH I-1
One of the first attempts at accounting for these forced-outages was to reduce each capacity increment by its nonperformance probability. A 200-MW unit performing 90% of the time was treated as a 180-MW unit performing 100% of the time. Table 2.4 summarizes the energy and cost totals for this example.

A more elegant means of incorporating forced-outages in production scheduling has been developed (10,19) and is portrayed as Example 3 in Figure 2.14. The abscissa has been relabeled the equivalent load $P_e$ signifying the stochastic or random nature of those units on forced-outages. The original normalized customer load-duration curve has been relabeled $F_D$, the "direct" customer demand to signify that each increment is directly responsible for satisfying customers within its section of the curve. However, if increment $V-2$ is off-the-line due to a forced-outage, increments of other units higher in the loading order (i.e., to its right) possess excess capacity capable of satisfying the customers $V-2$ is temporarily failing to serve. These customers are the direct responsibility of $V-2$ but are also the indirect responsibility of the other units. This additional indirect demand on all partially loaded unit increments is indicated by $F_I$. The resultant total equivalent demand $F_e$ on each increment (derived in detail in Chapter 3) is given by

$$F_e(P_e) = F_D(P_e) + F_I(P_e)$$  \hspace{1cm} (2.23)

Forced-outages affect not only the demand on each increment, but also the increment's production. If the unit only performs 90% of the time, then it is expected that only 90% of its demand will be served. Recalling from Section 2.1.2.2 that $p_r$ is the unit's performance probability, Equation (2.19) becomes,
TABLE 2.4

Example 2 on Reference Utility System:
"Deterministic Model (Reduced Capacities)"

(See Appendix C for further details.)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Increment</th>
<th>Position in Loading Order</th>
<th>Increment Energy $E_{ri}$ (GWH)</th>
<th>Increment Cost $X_{ri}$ ($10^3 \ $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>9</td>
<td>2.51</td>
<td>40.7</td>
</tr>
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<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>4</td>
<td>69.35</td>
<td>381.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
<td>5.81</td>
<td>24.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>III</td>
<td>1</td>
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<td>65.70</td>
<td>149.8</td>
</tr>
<tr>
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<td>2</td>
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<td>108.82</td>
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</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>1</td>
<td>3</td>
<td>131.40</td>
<td>515.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7</td>
<td>79.85</td>
<td>265.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>1</td>
<td>1</td>
<td>186.15</td>
<td>418.8</td>
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<td>2</td>
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<td>511.8</td>
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</tr>
<tr>
<td>Utility Production</td>
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<td>2514.2</td>
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<tr>
<td>Emergency Purchases (at 10$/MWH)</td>
<td></td>
<td></td>
<td>0.11</td>
<td>1.1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>949.00</td>
<td>2515.3</td>
</tr>
</tbody>
</table>

Loss-of-Load Probability, LOLP = 1.25%
Figure 2.14

Production Scheduling for Example 3 (With Forced-Outages)

- $P_e$, EQUIVALENT LOAD (Mw)
- $F_e$, EQUIVALENT LOAD-DURATION
- $F_D$, DIRECT LOAD-DURATION
- $F_I$, INDIRECT LOAD-DURATION
- $A_I$
- $A_D$
- $A_U$

Legend:
- $A_uT = D_u = 30.11$ GWH
- $LOLP = 0.1565$
- $K_I = INSTALLED\ CAPACITY$

- 186.15 GWH PRODUCTION
- II-1
- III-1
- IV-1
- V-1
- V-2
- IX-2
- II-2
- I-1
- A_u

Probabilities:
- $P_e \geq 0.00$
- $P_e \geq 0.25$
- $P_e \geq 0.50$
- $P_e \geq 0.75$
- $P_e \geq 1.00$
\[ E_{ri} = T' P_r \int_{P_{ri}}^{P_{ri} + \Delta K_{ri}} F_e (P_e) dP_e \] (2.24)

For this more general case, Equation (2.24) replaces Equation (2.41) for \( E_{ri} \). However, Equations (2.20) to (2.22) remain unchanged.

Table 2.5 presents the production and cost summary for the Reference System as loaded in Figure 2.14. Notice that, in contrast to Figure 2.12 where peaking Unit I was not utilized to meet any direct demand, in Examples 2 and 3 the unit is subject to some indirect demand due to forced-outages of the other four units. Furthermore, some indirect customer demand extends beyond the available installed (on-line) capacity,

\[ K'_T = \sum K_{ri} \] (2.25)

As one measure of system reliability, \( D_U \) represents the energy unserved by the system's resources,

\[ D_U = T' \int_{K'_T}^{\infty} F_e (P_e) dP_e \] (2.26)

"Expected unserviced energy... is the expected curtailment or, more realistically, the expected emergency support required during" the time period (49).

Along with \( D_U \), another measure of the system's reliability is the LOLP "loss-of-load-probability,"

\[ \text{LOLP} = F_e (K'_T) \] (2.27)

the fraction of time the utility is unable to serve its customers with its own resources.
TABLE 2.5

Example 3 on Reference Utility System:
"Probabilistic Model (With Forced-Outages)"

(See Appendix C for further details.)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Increment</th>
<th>Position in Loading Order</th>
<th>Increment Energy $E_{ri}$ (GWH)</th>
<th>Increment Cost $X_{ri}$ ($10^3$ $$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>9</td>
<td>11.93</td>
<td>193.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>4</td>
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<td>III</td>
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<td>65.70</td>
<td>149.8</td>
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<td>Utility Production</td>
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<td>2600.4</td>
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<tr>
<td></td>
<td>Emergency Purchases (at 10$/MWH)</td>
<td>30.11</td>
<td>301.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>949.00</td>
<td>2901.5</td>
<td></td>
</tr>
</tbody>
</table>

Loss-of-Load Probability, LOLP = 15.6%
The quantitative details of Chapter 3 underlying the above discussion center around the calculation of $F_e$.

Far more germane to the current topic is how other unit types are handled by this model. As for fast-start peaking units, their high fuel cost places them very high in the loading order, but, when their turn finally comes, they are represented exactly like fossil units.

Nuclear units, with very low fuel costs, are also treated like fossil units but they come very early in the loading order, provided each has sufficient reactivity inventory to supply the resulting energy requirements. If not, they are treated like the scarce resource hydro units in the following Section 2.2.2.

2.2.2 Hydro Units

The important characteristic of hydro unit scheduling is making optimum use of a free, but scarce, resource. To do this requires finding that place in the loading order (see Figure 2.15) that utilizes all the available hydro energy while displacing the most costly fossil fuel possible. This is the same process often interpreted as "peak-shaving" the system demand (51).

In terms of Equation (2.24), the optimum hydro loading point $P^*$ is determined such that,

$$E_H = T'p_H \int_{P^*}^{P^*+K_H} F_e(P_e) \, dP_e \quad (2.28)$$

The cost of $E_H$ is zero, but by utilizing $E_H$ in this manner, each hydro megawatthour has been used to displace the most expensive fossil energy possible and thereby saving the maximum amount of money.
Figure 2.15

Hydro Unit Production Scheduling

F(D) - DIRECT LOAD-DURATION

F(e) - EQUIVALENT LOAD-DURATION

\[ \text{AREA} = \frac{E_H}{p_H \cdot T'} \]

\[ F_e \cdot \text{EQUIVALENT LOAD-DURATION} \]
Determining the hydro's position in the loading order given $E_H$ is not difficult. The much more difficult question to answer is how much of the year's forecasted hydro resources to allocate to the period in question—i.e., determining $E_H$ itself. Large scale computer programs (51) are required to tackle this problem on a realistic mixed fossil-hydro system. In order to avoid the hydro complexities in this early nuclear power management development work, hydro units were not included in this study.

2.2.3 Pumped-Hydro Units

The most complicated of all, pumped-hydro unit production scheduling requires not only hydro-type utilization of a fixed energy resource, but also involves the pumping of that resource into the reservoir prior to the generation. Figure 2.16 portrays the situation. Pumping involves an added direct demand on nonfully loaded increments low in the loading order, while generating involves using the stored energy to displace more expensive fossil equipment high in the order. If $\eta_P$ and $\eta_G$ are the net efficiencies in the pumping and generating modes, respectively, pumping is continued until the last increment of pumping energy costing $\lambda_P$ just breaks even displacing an associated increment of generation saving $\lambda_G$. That is, pumping continues until,

$$\lambda_G = \frac{\lambda_P}{\eta_P \eta_G}$$  \hspace{1cm} (2.29)

However, this is subject to the constraint that the upper level reservoir capacity is not exceeded before pumping is terminated.

As with hydro units, pumped-hydro units were not included for further consideration in this initial development effort to avoid unnecessary complexity.
Figure 2.16

Pumped-Hydro Unit Production Scheduling

- **Customer Minimum Load**: $\lambda_p$
- **Direct Load-Duration**: $F_D$
- **Equivalent Load-Duration**: $F_e$
- **Energy Conversion Losses**: $A_G = \eta P_G A_P$
- **Costing**: $A_P$
- **Saving**: $P_G$

**Axes**:
- $P_e$: Equivalent Load (MW)
- $F_e$: Probability ($P_e \geq$)

**Key Values**:
- $0.75 \leq F_e \leq 1.00$
- $0.00 \leq P_e \leq 2000$

- **KP**: Point where $F_e = 0.75$
- **L**: Point where $F_e = 0.50$
- **P**: Point where $F_e = 0.25$
- **Q**: Point where $F_e = 0.00$
2.3 Complexities of Nuclear Power

The cost of fossil fuel is simply the cost of coal or oil plus shipping charges. Assuming a constant coal stockpile, newly delivered coal is burned immediately. From mine to ash, fossil fuel consumption requires only a matter of days.

Nuclear fuel, on the other hand, requires years to account for all cost components. Mining and enrichment occur nine months or more before insertion in the reactor. During the three years or more of irradiation, the energy potential is slowly extracted not only from this fuel batch but also from two or so others in the core. Three months or more after discharge, reprocessing occurs and fissile isotope credits are received. (Appendix H treats nuclear fuel cycle costs in more detail.) The net result is that the cost of a reactor's fuel over a time span of \( C \) cycles is a nonlinear, nonseparable function of the \( E_{rc} \) energy produced in each irradiation cycle,

\[
\overline{TC}_r = \overline{TC}_r(E_{r1}, E_{r2}, \ldots, E_{rC})
\]

(2.30)

Qualitatively, the nonlinearity,

\[
\overline{TC}_r \neq c_{r0} + c_{r1} \cdot E_{r1} + c_{r2} \cdot E_{r2} + \ldots + c_{rC} \cdot E_{rC}
\]

(2.31)

results from the fact that, given the refueling batch fractions, cycle energy is approximately linear in feed enrichment, but the cost of this enrichment (i.e., separative work requirement) is nonlinear.

Preventing a more general uncoupling of the cycle energies,

\[
\overline{TC}_r \neq C_{r0} + C_{r1}(E_{r1}) + C_{r2}(E_{r2}) + \ldots + C_{rC}(E_{rC})
\]

(2.32)

is the multi-irradiation (multi-zone) nature of today's LWR refueling schemes. The specification of reload enrichments requires not only
reactivity allowance for the next cycle, but succeeding ones as well. In summary, to calculate nuclear fuel costs, the cycle energies to the horizon of interest must be known.

In the early years of nuclear power, this stringent requirement did not pose a problem for conventional production scheduling models. With only a single nuclear plant on the system (see Figure 2.17), base-load operation was possible. That is, nuclear units were operated at full capacity whenever they were available. In addition, annual refueling meshed nicely with fossil maintenance plans and appeared to be reasonably economical. For the base-load ($F_e = 1$) case, Equation (2.24) reduced to

$$E_{rc} = p_r T'_r K_r$$

(2.33)

for all cycles. If $T'_r$ was constant, the cycles energies to the horizon were the same and reactor steady-state fuel costs could be calculated and used for all cycles.

However, as nuclear capacity on the system increased, two problems became apparent. First, not all nuclear units could be base-loaded if total nuclear capacity was greater than the minimum load as in Figure 2.17. Equation (2.33) was no longer valid because the nuclear portion of the load-duration curve was no longer equal to 1.0 for all nuclear units. Which nuclear unit should occupy the base-load position? Inter-nuclear incremental cost competition had surfaced for the first time. Only rough estimates of nuclear fuel costs had been necessary to decide that all nuclear equipment was cheaper than all fossil equipment, but very refined costs were now needed to decide nuclear unit A versus nuclear unit B.
Figure 2.17

Nuclear Capacity Greater than Minimum Load

- $F_e$, Probability ($P_e$)
- $P_e$, Equivalent Load (MW)
- $F_D$, Non-Nuclear Capacity
- Minimum Load
- First 600 MW Nuclear Unit
- Second 600 MW Nuclear Unit
- Shaded Area
Secondly, annual refueling created scheduling problems when each nuclear unit had to be refueled within every scheduling window. Coupled with decreasing nuclear load demand \( F_e \), what was the optimum cycle length for each reactor?

The net result was that cycle energies were no longer easily specified out to the horizon. The nuclear complications rendered previous utility system optimization models obsolete in the sense that operating plans based on them might be far from optimal.

The nuclear power management model to be put forth in Section 2.5 was developed to provide a modern model for utility system optimization, capable of handling nuclear plants explicitly. To do this, it must accurately predict cycle energies out to the horizon.

2.4 Comparison of Fossil and Nuclear Utility System Optimization

Incremental cost techniques for optimized fossil system dispatching (43,48) have been in use for many years. As Section 2.3 pointed out, nuclear plants present new problems due to the long-range time coupling inherent in the nuclear fuel cycle. Widmer et al. (67-59) optimized fossil-nuclear systems using nuclear incremental costs defined much differently from those of fossil plants. This section presents a parallel treatment of both fossil and nuclear incremental costs in order to point out the contrasting assumptions and results.

Consider the following general problem:

Minimize total system cost (i.e., revenue requirements) from time 0 (zero) to the end of the horizon \( Z \) (on the order of ten years) for a system containing \( R \) generating units.
Fuel for each unit is assumed to be provided under several consecutive fuel contracts. The objective function is then:

\[
\text{Minimize } \overline{TC} = \sum_{r=1}^{R} \overline{TC}_r(\Theta_{r1}, \Theta_{r2}, \Theta_{r3}, \ldots) \tag{2.34}
\]

subject to the load constraint,

\[
\sum_{r=1}^{R} P_r(t) = P(t) \tag{2.35}
\]

If \( H_r(P_r) \) represents the instantaneous heat input rate at power level \( P_r \) for the \( r \)th unit, then from the end of the previous contract, \( \tau_{r,c-1} \), to the end of current contract, \( \tau_{rc} \), the plant consumes thermal energy equivalent to

\[
\Theta_{rc} = \int_{\tau_{r,c-1}}^{\tau_{rc}} H_r(P_r) \, dt \tag{2.36}
\]

2.4.1 Incremental Costs on All Fossil System

For fossil units, two important assumptions come into play:

a) the various fuel supply contracts for each generating unit are uncoupled:

\[
\overline{TC}_r(\Theta_{r1}, \Theta_{r2}, \ldots) = \overline{TC}_{r1}(\Theta_{r1}) + \overline{TC}_{r2}(\Theta_{r2}) + \ldots \tag{2.37}
\]

and

b) the contract total cost \( \overline{TC}_{rc} \) is linear in \( \Theta_{rc} \):

\[
\overline{TC}_{rc} = \overline{TC}_{rc}^* + \phi_{rc} \cdot \Theta_{rc} \tag{2.38}
\]

where \( \phi_{rc} \) = levelized incremental thermal energy unit cost.

For an all fossil system, adding all \( C \) contracts for all the \( R \) units yields the objective function:

\[
\overline{TC} = \sum_{r=1}^{R} \sum_{c=1}^{C} \left\{ \overline{TC}_{rc}^* + \phi_{rc} \int_{\tau_{r,c-1}}^{\tau_{rc}} H_r(P_r) \, dt \right\} \tag{2.39}
\]
Since one summation is over all contracts (i.e., cycles), all time from 0 to \(Z\) is included and that summation may be replaced by an integral over \(t\). Defining
\[
\overline{TC}^\circ = \sum_{r} \sum_{c} \overline{TC}_{rc}^\circ
\]
then
\[
\overline{TC} = \overline{TC}^\circ + \int_{0}^{Z} \left\{ \sum_{c} \overline{\phi}_{rc} H_{r}(P_r) \right\} dt
\]
or more generally,
\[
\overline{TC} = \overline{TC}^\circ + \int_{0}^{Z} f(t; P_1(t), P_2(t), \ldots) dt
\]

Since the objective function is a definite integral over \(t\), the calculus of variations (32) allows immediate reduction of the problem. Employing the integrand of Equation (2.42) and the load constraint Equation (2.35) to form the auxiliary function \(\psi_F\),
\[
\psi_F = f(t; \text{all } P_r; \text{no derivatives } \dot{P}_r) + \lambda_F(t) \left\{ P(t) - \sum_{r} P_r \right\}
\]
Immediately, the optimum behavior of each \(P_r(t)\) is given by Euler's equation:
\[
\frac{d}{dt} \left\{ \frac{\partial \psi_F}{\partial \dot{P}_r} \right\} - \frac{\partial \psi_F}{\partial P_r} = 0
\]
Since there is no dependence of \(\psi_F\) on \(\dot{P}_r\), Equation (2.44) reduces to
\[
\frac{\partial \psi_F}{\partial P_r} = 0 = \frac{\partial f(...)}{\partial P_r} - \lambda_F(t)
\]
Substituting for \(f(...)\) using Equation (2.41) and rearranging,
\[
\lambda_F(t) = \overline{\phi}_{rc} \frac{\partial H_r(P_r)}{\partial P_r}
\]
Since \( \frac{\partial H_r(P_r)}{\partial P_r} \) equals the incremental heat rate at \( P_r \), \( h_{inc_r}(P_r) \),

\[
\lambda_{F}(t) = \phi_{rc} \cdot h_{inc_r}(P_r) \quad (2.47)
\]

for all \( R \) units at the same time \( t \), subject to Equation (2.35).

The Lagrangian multiplier \( \lambda_{F}(t) \) represents the time-varying incremental energy cost (i.e., proportional to \( \phi_{rc} \) discounted dollars over undiscounted energy) at which all fossil units on the system should be operating for minimum system cost. Equation (2.47) is the same result Kirchmayer obtained (43) with the a priori knowledge that instantaneous optimization gave the long-term optimum rather than beginning with the long-term objective function, Equation (2.34).

Typical values for present day fossil systems involve unit fuel costs of 25 to 50 \( \xi \)/Mega BTU and incremental heat rates as low as 8000 BTU/kwhe at night to over 15,000 BTU/kwhe (8 to 15 Mega BTU/MWH) during the hours of peak demand. System incremental fossil fuel cost thus varies on a daily basis from 2.0 to 7.5 \$/MWH.

2.4.2 Incremental Costs on All Nuclear System

For nuclear reactors, which have coupled, nonlinear cycle costs, the two assumptions made for fossil units [Equations (2.37) and (2.38)] do not hold. However, the data of Figure 2.18 indicates that for today's LWR's, the incremental heat rate of a nuclear plant is approximately constant over the operating range of interest (40% to 100% of full power),

\[
h_{inc_r} \neq f(P_r) \quad (2.48)
\]

Extrapolating the heat rate curve \( H_r(P_r) \) back to \( P_r = 0 \) at the constant incremental heat rate \( h_{inc_r} \),

\[
H_r(P_r) = H_r^* + h_{inc_r} \cdot P_r \quad \text{for} \ P_r > 0 \quad (2.49)
\]
Figure 2.18

Incremental Heat Rates for Typical Light Water Reactor

- 20% (Actual) Limiting Minimum Load
- With 30% (Effective) Operational Minimum Load
- With 40% (Effective) Oper. Minimum Load

Ref: After (13) and (44)
Since $P_r$ (and hence $H_r = 0$) during the refueling downtime following shutdown at $\tau_r$, Equation (2.36) need only be integrated over the available generating hours $T'_{rc}$.

$$\Theta_{rc} = \int_{T_r - T'_{rc}}^{T_{rc}} \left( H_r^o + h_{incr} \cdot P_r \right) dt$$

(2.50)

Assuming the nuclear units to be "must-run" units (see Section 2.4.3), they can be expected to perform at least at minimum load (i.e., $P_r \gg 0$) for $p_r \cdot T'_{rc}$ hours.

Hence,

$$\Theta_{rc} = H_r^o \cdot P_r \cdot T'_{rc} + h_{incr} \int_{T_r - T'_{rc}}^{T_{rc}} P_r dt$$

(2.51)

or,

$$\Theta_{rc} = H_r^o \cdot P_r \cdot T'_rc + h_{incr} \cdot E_{rc}$$

(2.52)

Since $\Theta_{rc}$ is linear in $E_{rc}$, direct substitution into the objective function is possible:

$$\overline{TC} = \sum_{r=1}^{R} \overline{TC}_r(\Theta_{r1}, \Theta_{r2}, \ldots) = \sum_{r=1}^{R} \overline{TC}_r(E_{r1}, E_{r2}, \ldots)$$

(2.53)

In order to transform the customer loads into corresponding energy units, the time horizon is segmented into $Z$ convenient time periods on the order of weeks. Then, the right-hand side of Equation (2.35) is integrated over each time period to yield period energy demand,

$$D_p = \int_{t_{p-1}}^{t_p} P(t) dt$$

(2.54)

Assuming there are enough nuclear units on the system to prevent loss-of-load, the period energy demand must be generated by the $R$ units in that period,
During a particular reactor-cycle, the energy must be the sum of the reactor's production in each of the included periods,

\[ E_{rc} = \sum E_{rcp} \]  

(2.56)

Thus, the independent variables in Equation (2.53) can be further subdivided into period energy productions,

\[ \overline{TC} = \sum \overline{TC}_r \left( \{E_{rcp}\}_r \right) \]  

(2.57)

To form the \( \psi_N \) auxiliary function of Equation (2.57), the constraints [Equation (2.55)] are incorporated using a \( \lambda_{Np} \) Lagrangian constant for each period,

\[ \psi_N = \sum \overline{TC}_r \left( \{E_{rcp}\}_r \right) + \sum \lambda_{Np} \cdot \left( D_p - \sum E_{rcp} \right) \]  

(2.58)

which is only a function of the \( E_{rcp} \) set, \( \{E_{rcp}\}_r \).

For \( \psi_N \) to be a relative minimum (31), the following must hold for all \( r \), all \( c \) and all \( p \):

\[ \frac{\partial \psi_N}{\partial E_{rcp}} = 0 = \frac{\partial \overline{TC}_r}{\partial E_{rcp}} - \lambda_{Np} \]  

(2.59)

Therefore, during each period of the optimum,

\[ \lambda_{Np} = \frac{\partial \overline{TC}_r}{\partial E_{rcp}} \]  

(2.60)

for the pertinent cycles of each reactor, subject to Equation (2.55).

Since the \( E_{rcp} \) sum linearly to give the cycle energy \( E_{rc} \) [Equation (2.56)],
the optimality condition Equation (2.60) can be restated as

\[ \lambda_N = \frac{\partial TC_r}{\partial E_{rc}} \]  

(2.62)

The Lagrangian constant \( \lambda_n \) (with units identical to \( \lambda_F \), discounted dollars over undiscounted energy) represents the incremental energy cost at which the pertinent refueling cycle of each nuclear unit should be designed and operated. The coupling of nuclear energies in the objective function prevents the simplifications made in the fossil case. However, the approximately constant incremental heat rate of today's nuclear units (above 40% of capacity) permits a different simplification and leads to Equation (2.62).

To contrast Equations (2.47) and (2.62) in more general terms, consider that

\[ \lambda_N = \frac{\partial TC_r}{\partial E_{rc}} = \frac{\partial TC_r}{\partial \Theta_{rc}} \frac{d \Theta_{rc}}{d E_{rc}} \]  

(2.63)

Differentiating Equation (2.52),

\[ \frac{d \Theta_{rc}}{d E_{rc}} = h_{inc_r} \]  

(2.64)

Hence, for nuclear units,

\[ \lambda_N = \frac{\partial TC_r}{\partial \Theta_{rc}} \cdot h_{inc_r} \]  

(2.65)

resulting in nuclear dispatching on a cycle-by-cycle basis using energy-related incremental costs.
Fossil units, on the other hand, are dispatched using instantaneous incremental costs related to power level [Equation (2.47)],

\[ \lambda_{F}(t) = \phi_{rc} h_{inc}^{r}(P_{r}(t)) \]  

(2.66)

Substituting the definition of \( h_{inc}^{r} \) [Equation (2.3)],

\[ \lambda_{F}(t) = \phi_{rc} \cdot \frac{dH_{r}(P_{r})}{dP_{r}} \]  

(2.67)

Comparing Equations (2.65) and (2.67), the former is in terms of energy because the "incremental" effect or derivative is in the fuel cost component related to cycle energy, not the incremental heat rate \( h_{inc}^{r} \) which is assumed constant for any power level. The reverse is true for the latter's fossil incremental cost. The \( \lambda_{F} \) is power level dependent because the \( h_{inc}^{r} \) is recognized as a function of \( P_{r}(t) \); the fuel cost component \( \frac{\partial T_{r}}{\partial \Theta_{rc}} \) is assumed a constant \( \phi_{rc} \) independent of cycle energy.

Another conclusion regarding nuclear incremental costs can be deduced by considering the cycle-to-cycle overlap of two reactors as in Figure 2.19. In the \( p^{th} \) period, both reactors have the same incremental cost per Equation (2.60). Going one step further, Equations (2.56) and (2.62) indicate that within the range of periods in the companion cycles, the incremental cost remains the same. Finally, as the cycle ends for Reactor 1, \( \lambda_{N}^{p} \) remains at the same level due to Reactor 2. But, Equation (2.62) states that Reactor 1's next cycle should also be designed at this same level to maintain the equality. Thus, the overlapping of reactor-cycles creates a constant \( \lambda_{rc} \) regardless of reactor and cycle.

Consequently,

\[ \lambda_{N}^{p} = \lambda_{N} = \text{constant for all } p \]  

(2.68)
Figure 2.19

Consequences of Period Incremental Cost Equality

\( \lambda_{np} \) PERIOD EQUALITY OF EQ. (2.60)

\( \lambda_{np} \) PERIOD \( p \)

TIME

REFUELING OUTAGE

\( \lambda_{np} = \lambda_{1c} \)

\( \lambda_{np} = \lambda_{2c} \)

CYCLE EQUALITY OF Eqs. (2.56) AND (2.62)

\( \lambda_{n} \)

\( \lambda_{np} = \lambda_{1c} = \lambda_{2c} = \lambda_{n} \)

UNIVERSAL EQUALITY OF EQ. (2.68)
and

\[ \lambda_N = \frac{\partial TC_r}{\partial E_{rc}} \]  \hspace{1cm} (2.69)

for all \( r \) and all \( c \) simultaneously.

A consequence of Equation (2.69) is that steady-state would never be reached. Due to the discounting of dollars, but not energy, it becomes profitable to generate more and more energy in each succeeding cycle, relying on the increasing discount factor to appropriately reduce the additional undiscounted cost. This is the case for cycles 1 through 3 of Figure 2.20. While Equation (2.69) indicates the profitable thing-to-do, it does not indicate how feasible it is. Cycles 4, 5 and 6 of Figure 2.20 are examples of steady-state designs (with decreasing incremental costs) being forced by a constraint, namely, that the capacity factor cannot be greater than one. In other words, generation cannot be postponed. Demand must be satisfied instantaneously, not four years later. Generation can be shifted from one reactor to another on a day-to-day basis but the total production each period must be met [Equation (2.55)].

The net result is the primary Conclusion I [Equation (2.70)], relating a strong dependence between pertinent cycle incremental costs for each reactor during each period and a secondary Conclusion II [Equation (2.71)] relating an idealized state that may not be attainable:

**Conclusion I:**

At the optimum reactor-cycle energies,

\[ \lambda_N = \frac{\partial TC_r}{\partial E_{rc}} \]  \hspace{1cm} (2.70)

during each period for the pertinent cycle of each reactor.
Figure 2-20
Consequences of Conclusion II Incremental Costs versus Cycle Energy

430 MW PWR [AFTER (57)]
ANNUAL INSTANTANEOUS REFUELING

If $\lambda_N = 0.95$

DISCOUNTED 0 YEARS AT 7%

LOAD FACTOR

INCREMENral COST ($/MWh)

CYLE ENERGY ($10^3$ GWH)
Conclusion II:

At the optimum reactor-cycle energies,

\[ \lambda_N = \frac{\partial TC}{\partial E_{rc}} \]  

(2.71)

for all periods, all cycle and all reactors simultaneously, subject to physical constraints.

As for typical values of \( \lambda_{N_p} \) and \( \lambda_N \), the results of Widmer (57), Kearney (41) and Watt (55) as well as Section 5. 6. 3 indicate optimum mid-range nuclear incremental costs in the range of 0.9 to 1.6 $/MWH.

2.4.3 Optimization of a Mixed System

The two previous sections have indicated how an all fossil or an all nuclear system would meet the same loads at minimum total system cost. This section endeavors to show the reasoning behind segmenting the more realistic mixed fossil-nuclear system into an equivalent "all fossil plus all nuclear" system such that,

\[ DT_p = EF_p + EN_p + DU_p \]  

(2.72)

Given the normalized customer load-duration curve and the available generating equipment, a startup and loading order is required by the production scheduling model. The first consideration is the placement of unit increments under the "knee" of the load-duration curve, i.e., below the minimum load (see Figure 2.12) where they will be operated even during periods of lowest system demand, such as the early morning hours. These unit increments are typically the minimum loads on all of the large units (e.g., rated capacity ≥ 300 MW). If such units were shut down overnight due to economics alone, minimum shutdown times and other engineering
problems might prevent the unit from being in service when it was needed for the next day's peak. Losing such a large unit creates reliability problems. Thus, the operating philosophy is that all large units must be running at least at minimum load if possible. If the minimum load is too low to permit this, either the smallest of the "must-run" units is shut down or its excess capacity is sold to neighboring utilities on an hour-by-hour economy interchange basis.

For a mixed fossil-nuclear system, this must-run philosophy results in grouping all nuclear minimums at the lowest point in the startup and loading order. Next comes the must-run fossil minimums in order of decreasing size. Figure 2.12 portrayed the must-run units in Examples 1 to 3 for a lower limit of 200 MW.

The startup and loading order for the rest of the system is determined by noting two important points. First, on a time scale where reload fuel is being designed, nuclear units are not energy-limited, and nuclear production should not be scheduled as scarce resource. Secondly, even with fossil fuel costing as little as 25 c/MegaBTU, the best-plant fossil incremental costs are at least 2.0 $/MWH (see Section 2.4.1). Since even the highest nuclear incremental fuel costs are less than 1.6 $/MWH (see Section 5.6.3), nuclear power should be operated so as to displace maximum fossil energy. In other words, the greatest potential for cost savings in each period is in maximizing nuclear production \( E_{N_p} \) vis-à-vis fossil production \( E_{p} \). (\( D_U \) is invariant given the on-line equipment.) Mathematically, total period cost is a minimum when

\[
D_T = E_{min}^F + E_{max}^N + D_U
\]  

(2.73)

The above loading order does just that, maximizing \( E_{N_p} \) and resulting in \( N_p \).
the system's nuclear potential for the period,

\[ N_p = E_{\text{max}}^N \]  \hspace{1cm} (2.74)

Thus, after starting up and raising to minimum power the must-run units that are not shut down regularly, all nuclear plants are loaded to full power in accordance with system demands. As demand continues to increase, all the remaining fossil power is loaded in order of increasing incremental cost.

Figure 2.11 portrayed such a startup and loading order applied to the Reference System in Examples 1 to 3. It is now a simple matter to separate the "all nuclear" system from the "all fossil" system. Performing the above for each time period of a study thus separates the fossil and nuclear portions of the system. These two subsystems can then be optimized using the techniques of Sections 2.4.1 and 2.4.2, respectively.

The key assumption leading to the fossil-nuclear dichotomy, bears repeating since it is the basis of the entire nuclear power management model presented in the next section.

\[ \lambda_N < \lambda_F(t) \text{ for all } t \text{ and } p \]  \hspace{1cm} (2.75)

2.5 A Nuclear Power Management Multi-Year Model

A nuclear power management multi-year model currently under development \((23,34)\) contains four submodels as presented in Figure 2.21. The overall model's purpose is to supply the utility system planner with the following outputs:

1. Optimum schedule for fossil maintenance and nuclear refueling,
2. Associated optimum production schedule and
3. The resultant fuel requirements.
Figure 2.21

Nuclear Power Management
Multi-Year Model

REFUELING AND MAINTENANCE MODEL (RAMM)

SYSTEM INTEGRATION MODEL (SIM)

SYSTEM OPTIMIZATION MODEL (SOM)

CORE SIMULATION AND OPTIMIZATION MODELS (CORSOMs)

OPTIMUM REFUELING, MAINTENANCE AND PRODUCTION SCHEDULE MINIMUM TOTAL COST
Operation of the overall model begins within the Refueling and Maintenance Model (RAMM). Incorporating such inputs as load forecasts, maintenance requirements and scheduling constraints, the RAMM determines a number of feasible multi-year refueling and maintenance schedules. Each schedule is a mutually exclusive, alternative mode of operating the entire system over the multi-year horizon. The purpose of the rest of the overall model is to determine which of the possible alternative strategies results in minimum total cost.

Strategy-by-strategy evaluation begins in the System Integration Model (SIM). For each strategy, the SIM integrates the utility's available equipment, operating practices, etc. into a realistic utility simulation model. Production scheduling is optimized so as to meet customer load demand by maximizing nuclear energy and minimizing fossil energy and fossil cost (see Section 2.4.3).

The task of the System Optimization Model (SOM) is then to optimize the operation of the nuclear portion of the system (see Section 2.4.2) so that the nuclear energy $E_{\text{Nuclear}}$ is produced at minimum cost $\$_{\text{Nuclear}}$. To do this, the SOM postulates reactor-by-reactor multi-year production schedules which are then passed to Core Simulation and Optimization Models (CORSOM's) for each reactor unit or type (PWR, BWR, LMFBR, etc.). With each production schedule specified to the horizon (see Section 2.3), each CORSOM is then able to optimize its reload parameters of batch size and enrichment, minimizing the total fuel cost for the particular reactor. In addition, the CORSOM calculates nuclear incremental costs for each of the cycles.

With all reactors optimized for the given schedules, the SOM begins a second iteration by using the CORSOM's incremental nuclear energy
costs to postulate a better reactor-by-reactor multi-year production schedule. Iterations continue until the system-wide production schedule converges, giving minimum system nuclear cost $\text{Nuclear}$. The total system cost for the particular refueling and maintenance strategy under investigation is then merely the sum of $\text{Fossil}$ and $\text{Nuclear}$. After evaluating all possible alternative strategies in this manner, the overall optimum system strategy is the one resulting in the minimum total system cost.

Though the above discussion and, in fact, this entire work assumes only fossil and nuclear equipment exist on the system, the general structure of the overall model holds even if hydro and pumped-hydro equipment have been installed.

The development of the complete nuclear power management multi-year model is a very large task. However, the four submodels represent convenient building blocks suitable for somewhat independent development. However, model interface problems must be considered. Ideally, the models ought to be coupled together like the boxcars of a train, not nailed together like the tracks.

In the context of the Commonwealth Edison-sponsored utility system optimization research project at the Massachusetts Institute of Technology, development of a RAMM was assumed by the project sponsor (20). Development of a pressurized water reactor CORSOM was undertaken at MIT by Kearney (41) and Watt (55). The concluding sections of this chapter emphasize these two models, indicating the important aspects relative to RAMM and CORSOM development and their interfacing with the rest of the model (see Figure 2.22). As the title indicates, the work reported here deals specifically with the development of the remaining SIM and SOM.
Figure 2.22 NUCLEAR POWER MANAGEMENT MULTI-YEAR MODEL
2.5.1 Refueling and Maintenance Model (RAMM)

Taking due account of the five inputs indicated in Figure 2.22, the RAMM's purpose is to generate possible alternative strategies for further investigation by the rest of the nuclear power management multi-year model.

The output of the RAMM is anticipated by the SIM in the form of either a set of downtime dates for each unit on the system or a period-by-period (on the order of one to four weeks per period) maintenance schedule indicating which units are down in each period.

Also desirable is a RAMM ranking of the strategies in order of anticipated desirability. That is, "ballpark" estimates of economics and reliability ought to indicate Strategy 1 is most likely to be optimum, while Strategy n (n ~ 100), though feasible, is highly unlikely to be economically attractive and/or a reliable operating scheme. Such a ranking would decrease computing requirements by permitting the detailed evaluation of only those strategies with a reasonable chance of competing for the optimum.

With regard to the testing of the nuclear power management model in Chapter 5, Sections 5.2 and 5.3.3 indicate the RAMM utilized in the evaluation.

2.5.2 System Integration Model (SIM)

Chapter 3 is devoted to a detailed discussion of the SIM and, in particular, the Booth-Baleriaux utility model.

2.5.3 System Optimization Model (SOM)

Chapter 4 is devoted to a detailed discussion of the SOM.
2.5.4 Core Simulation and Optimization Model (CORSOM)

At each iteration in Figure 2.22, the CORSOM accepts a new set of cycle energies (E's) for its reactor and, in point of fact, the same set of cycle lengths (T's) associated with the particular possible alternative strategy. After simulating core physics-depletion and optimizing the reload parameters (batch size and enrichment), it is required to return to the SOM only two specific types of information:

(1) the minimum total reactor fuel cost ($T_{Cr}$) and

(2) the nuclear incremental cost curve for each reactor reload batch,

\[
\lambda_{rc}(E_{rc}) = \frac{\partial T_{Cr}}{\partial E_{rc}}
\]  

(2.76)

Specific information about the fuel designs is not needed by the SOM. As long as each CORSOM is properly matched with the reactor unit index that it represents, the SOM does not care which unit indexes are PWR's, BWR's, HTGR's or fast breeders. Of course, management personnel need fuel design information and it must, therefore, be available in the printed output received directly from the CORSOM (at least, for the final fully-converged iteration).

The details of such a PWR core model can be found in the work of Kearney (41) while the techniques of incremental costing can also be found in the work of Widmer (57) and Watt (55).

With regard to the testing of the nuclear power management model in Chapter 5, Section 5.2 and Appendix H detail the CORSOM utilized in the evaluation.
CHAPTER 3

THE SYSTEM INTEGRATION MODEL

3.1 Overview of the SIM

Many aspects of the System Integration Model (SIM) have already been described in Chapter 2. The emphasis in the current chapter will be on detailing the Booth-Baleriaux probabilistic utility model and describing the calculation of the various cost components.

The SIM has as its basic purpose the simulation of multi-year utility operation. To do this, it must integrate the following information into a representative utility system model:

1. Forecasts of customer loads,
2. Generating equipment characteristics,
3. Forecasts of fuel costs,
4. Maintenance schedules and
5. Operating constraints.

To portray system operation more accurately, the multi-year horizon is divided into much smaller time periods, on the order of a few weeks. Periods shorter than a week create an undue computational burden. On the other hand, periods longer than a month are precluded by the necessity of discretely representing scheduled maintenance outages which are usually two to four weeks in length.
These time periods are then simulated individually in chronological sequence. Forecasted loads for each period (Item 1 above) are represented by a normalized customer load-duration curve such as the month on the Reference Utility System presented in Figure 2.9. Thermal energy costs (Item 3) are combined with the characteristics of the generating units per Equation (2.18) to yield unit incremental costs. Any unavailable units down due to scheduled maintenance (Item 4) are treated as non-existent for that period. The next step is the establishment of the startup and loading order (see Section 3.2) for the remaining on-line units. It is in this order that various operating constraints (Item 5), such as "spinning reserve" and "zone-loading" requirements are incorporated. Production scheduling of the resulting system representation is performed using the Booth-Baleriaux probabilistic utility system model (see Section 3.3).

The qualitative discussion of the Booth-Baleriaux model presented in Section 2.2.1 developed cost components for most of the required period expenditures enumerated in Section 2.1.3:

(1) $X_F = \text{Fossil fuel expense related to } E_F \text{ energy production},$

(2) $X_N = \text{Nuclear fuel expense related to } E_N \text{ energy production},$
(3) $X_S = \text{Combined fossil and nuclear startup-shutdown cost (not discussed in Chapter 2) and}$

(4) $X_U = \text{Expense related to } D_U \text{ emergency energy purchases.}$

Later, Section 2.3 pointed out that the complexities of nuclear power preclude \textit{a priori} knowledge of nuclear fuel costs $X_N$ except for the special case of all nuclear base-load operation. Nevertheless, by incorporating the nuclear versus fossil incremental cost argument of Section 2.4.3 to sub-optimize each period, the SIM is able to mark time by calculating in its place the system nuclear potential $N$ for each period. The responsibility for optimizing and costing inter-nuclear production of this energy rests with the System Optimization Model (SOM).

Even an \textit{a priori} estimate of unit nuclear fuel costs $\phi_{NR}$ is sufficiently accurate for the nuclear component of system startup-shutdown costs since $(X_S)_N$ represents only a small fraction of total nuclear production fuel cost $X_N$, 

$$ (X_S)_N \ll X_N $$

Furthermore, for nuclear units (all assumed to be must-run units), there are very few startup-shutdowns since the units are always running. Hence, nuclear startup cost is also much less than fossil startup cost,
Thus, an initial error in $\theta_N$ has a very small effect on total period expenses.

In summary, the actual period-by-period output of the SIM consists of:

1. $X_F = \text{Fossil fuel expense related to } E^\text{min}_F \text{ energy production (see Section 3.3)},$

2. $N = \text{Nuclear potential equal to } E^\text{max}_N \text{ energy production (see Section 3.3.3)},$

3. $X_S = \text{Combined fossil and nuclear startup-shut-down cost (see Section 3.4)}$ and

4. $X_U = \text{Expense related to } D_U \text{ emergency energy purchases (see Section 3.5)}.$

In addition to these outputs discussed in this chapter, the SOM of Chapter 4 requires various data related to the nuclear potential and each reactor's possible contributions to it. Discussion of these more subtle outputs is postponed until Section 4.2.

### 3.2 Determining Startup and Loading Order

The Booth-Baleriaux model to be discussed in Section 3.3 is an objective, mathematical algorithm for calculating energy production given a startup and loading order for the capacity increments. Thus, it is in determining this input loading order (sometimes referred to as the
"pecking order"), that the more subjective aspects of utility operating practices and constraints must be considered.

The goal is to determine for each period the startup and loading order that meets all operating constraints at minimum total cost. Ironically, startup-shutdown cost itself is not used in the multi-year model for determining the startup order. For one thing, total startup-shutdown cost is rarely as large as 1% of production fuel cost. In addition, accurate startup-shutdown cost prediction requires a daily or hourly model, as in the work of Joy (37, 38).

Though this cost component is not considered in determining the loading order prior to the Booth-Baleriaux simulation, Section 3.4 will discuss how $X_s$ is estimated from the model's output.

To determine the unit-by-unit startup order, minimum average fuel costs are determined by inspection of average heat rate data as in Figure 2.5.

$$\bar{\epsilon}_r^{\min} = \phi_r \bar{h}_r^{\min}$$

A tentative startup order can then be determined by plotting this data in ascending order of cost. Figure 3.1a presents such a startup order for the on-line units of a hypothetical utility system. This order is the most attractive economically (ignoring incremental effects due
Figure 3.1a
Optimum Economic Startup Order

Figure 3.1b
Optimum Constrained Startup Order

\[ e_{min}^{\text{ideal}} \]

\[ e_{r} \]

\[ \text{MINIMUM AVERAGE ENERGY COST ($/\text{MWh})} \]

\[ \text{IDEAL STARTUP POSITION} \]

\[ \text{CONSTRAINED STARTUP ORDER} \]

O MOVED UP (TO LEFT) IN STARTUP ORDER DUE TO CONSTRAINTS
to startup-shutdown cost itself).

However, various operating constraints alter the order. For instance, engineering and reliability constraints may dictate that some units are must-run units (see Section 2.4.3). Additional constraints related to the distribution of units, loads and transmission lines among geographical regions or zones may impose zone-loading requirements. Such constraints require a unit to be started earlier in the order so that utilization of the entire transmission system will remain approximately balanced. This not only reduces the probability of a transmission system outage, but also reduces the consequences should one occur. Figure 3.1b presents the final constrained startup order for the data of Figure 3.1a.

The first increments in the complete system loading order are, by definition, the minimum power levels of each must-run unit. As Figure 2.12 and Equation (2.33) indicate, the exact order below the minimum system load is arbitrary since all are base-loaded. In fact, the generally low level of nuclear fuel costs coupled with the must-run constraint for such large units is sufficient to permit the assumption that all nuclear minimums are base-loaded. Furthermore, the incremental cost argument of Section 2.4.3 justifies placing all of the upper nuclear increments, as a group, next in the order just to the right of the must-run increments. As it turns out (see Section
3.3.3), the exact intranuclear loading order for these upper increments is arbitrary, relieving the necessity of having precise nuclear incremental costs during the SIM's calculations.

Having assigned all nuclear capacity and all must-run fossil minimums, the incremental cost arguments of Sections 2.2.1 and 2.4.1 determine a complete, but tentative, startup and loading order. For determining the startup of remaining units, \( e_r^{\text{min}} \) represents unit \( r \)'s opportunity generating cost if the unit is on-line at the power level that minimizes \( F \). However, costing of the unit's first increment is performed using the \( e_{rl} \) out-of-pocket average cost [per Equations (2.18) and (2.21)].

\[
X_{rl} = e_{rl} E_{rl} \quad (3.4)
\]

The unit's upper increments are characterized by the usual \( \lambda_{rl} \).

Given the constrained startup order, the completed loading order is the economic optimum. However, actual operating practices may violate this ordering in the same way that the economic startup order was violated. For instance, a daily practice may involve bringing units up to minimum load a few hours early so that any minor startup problems can be alleviated and their capacity will be available when actually required. Another operating constraint
is the requirement for several hundred megawatts of spinning reserve in case a large unit suddenly trips off the line. Spinning reserve represents the readily available (on the order of minutes), uncommitted capacity of turbines already spinning, but generating at less than full capacity. Such a requirement necessitates earlier (uneconomical) startup of some units so that cheaper increments, previously comprising the spinning reserve, may be loaded (see Figure 3.2).

Because of their fast-start capability, peaking units are considered as a separate "stand-by reserve". As such, they need be committed only when their high fuel cost is economically justified.

With such operating constraints properly factored in, the startup and loading order for the period is complete. The evaluation of the period's resulting energy and cost components is the subject of the rest of this chapter.

3.3 Scheduling and Costing Production

3.3.1 Basics of Booth-Baleriaux Probabilistic Utility Simulation Model

3.3.1.1 Background

The Booth-Baleriaux probabilistic utility simulation model is a recent adaptation of previous deterministic utility models with new emphasis on the field of applied probability theory. Though the original 1967 paper on the
Figure 3.2

Example of Variation of Spinning Reserve as Units are Started up and Loaded

Spinning Reserve Requirement = 100 MW

ECONOMIC STARTUP OF 200 MW UNIT

ECONOMIC LOADING OF INCREMENTS

REQUIRED STARTUP OF 100 MW UNIT

REQUIRED STARTUP OF 150 MW UNIT
subject is a product of Baleriaux, et al. (10) of Belgium, Booth (17-19) of Australia deserves much of the credit for introducing and promoting the model in the United States.

Previous papers reporting on the Booth-Baleriaux model, including the work of Joy and Jenkins (39), have closely followed the development in the original paper. With due respect to these ground-breaking efforts, the following presentation leads to computational savings in terms of time and storage, and also follows a more direct line of reasoning.

The Booth-Baleriaux probabilistic utility model is based on the concept of equivalent load which embodies not only direct customer demands on a particular unit, but also the indirect demands left unsatisfied by previously loaded units when they are on forced-outages.

The equivalent load $P_e$ may be defined as

$$P_e = P_D + P_O$$

(3.5)

where

$P_D = \text{actual direct customer load demand, MW}$

$P_O = \text{system capacity on forced-outage that would be generating energy otherwise, MW}$

Capacity that is on forced-outage during what would otherwise have been reserve (i.e., economy) shutdown hours anyway
is not counted since the outage does not affect system generating operations.

In a probabilistic sense, $P_D$ is a random variable with a complementary cumulative distribution given by $F_D(P_D)$, the normalized customer load-duration curve. Since forced-outages are random, $P_0$ is also a random variable characterized by the performance probabilities of each unit. Thus, $P_e$ is also a random variable and the computation of its required complementary cumulative distribution function $F_e(P_e)$ involves the convolution of the distributions of $P_D$ and $P_0$ (26). Hence, $F_e(P_e)$ is the load-duration curve for the equivalent load $P_e$. The heuristic presentation here is limited to the common two-state model of forced-outages:

State 1: With probability $p$, the unit will perform at any output up to its rated capacity when called upon and

State 2: With probability $q$, the unit will not perform at all when called upon.

Thus,

$$p + q = 1 \quad (3.6)$$

A rigorous treatment of the more general case allowing for forced deratings (i.e., inability of the unit to perform at rated capacity, though partial output is possible), is presented in Appendix A.
To keep the numerical effort to a minimum while illustrating the principle, the detailed numerics of the Booth-Baleriaux convolution algorithm are first presented by way of a simple two-unit, single-increment example. ("Single increment" refers to the fact that each unit is treated as a single block of capacity). This model, the original contribution of Baleriaux, et al. (10), is the so-called "one-piece" Booth-Baleriaux model. Building on this, a more general "multi-piece" procedure (39) permitting the multiple increments to be scheduled separately is presented in Section 3.3.2.

3.3.1.2 Heuristic Derivation of Booth-Baleriaux Convolution using Two Unit, Single Increment Example

In order to derive the basic Booth-Baleriaux convolution equation, consider a 500 MW system consisting of Unit 1 (200 MW with \( p_1 = 70\% \)) and Unit 2 (300 MW with \( p_2 = 60\% \)). As displayed in Figure 3.3, the system is attempting to satisfy the indicated \( F_D \) customer load-duration curve abcde with a peak demand of 400 MW. For convenience, let the time period duration \( T' = 1 \) hour. Hence, total demand \( D_T = 250 \) MWH (area zabcdez).

Since Unit 1 is the first to come on line, the first step in the simulation is to compute its loading. Since there are no units to its left, the equivalent load as seen by Unit 1 is merely the direct customer demand \( F_D \). However, the unit performs only 70\% of the time. Thus, Unit 1 is
Figure 3.3

Complete Two Unit Booth-Baleriaux Example

<table>
<thead>
<tr>
<th>UNIT</th>
<th>RATED CAPACITY</th>
<th>PERF. PROB.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$K_1 = 200 \text{ MW}$</td>
<td>$p_1 = 70%$</td>
</tr>
<tr>
<td>2</td>
<td>$K_2 = 300 \text{ MW}$</td>
<td>$p_2 = 60%$</td>
</tr>
</tbody>
</table>
only able to generate 70% of the energy demanded from it (area $\text{Sabcsz}$),

$$E_i = T' p_1 \int_0^{K_1} F'_D(P_e) dP_e$$  \hspace{1cm} (3.7)

or

$$E_i = 1 \text{ hour} \times 0.7 \times 180 \frac{\text{MWH}}{\text{hour}} = 126 \text{ MWH}$$  \hspace{1cm} (3.8)

Unit 1 has been loaded according to $F'_D$, the equivalent load curve $F$ "without" an adjustment for Unit 1's outages ($= F^{WO}_1$). Unit 2, on the other hand, sees not only direct customer demand $F'_D$, but also indirect demand unsatisfied by Unit 1 while it was down due to a forced-outage. Thus, before loading Unit 2, Unit 1's outages must be "convolved" into $F^{WO}_1 (\equiv F_D)$ to yield $F^W_1$ (i.e., "with" an allowance for Unit 1's forced-outages).

To do this, it is necessary to consider the two states:

(1) Unit 1 performs, a state with the probability $p_1$ ($= 0.7$), and

(2) Unit 1 fails to perform, a state with the probability $q_1 = 1 - p_1$ ($= 0.3$).

Thus, a particular equivalent load, for example $P_e \geq 300 \text{ MW}$ can be arrived at in only two possible independent ways. The probability that the equivalent load $\geq 300 \text{ MW}$ is the
sum of the probabilities of each of the individual ways. When unit 1 performs, the probability that the equivalent load \( P_e \geq 300 \) MW is the product of the probability that unit 1 will perform \( (p_1) \) and the probability that the equivalent load will exceed 300 MW without an allowance for outage of unit 1 \( [F^{WO}_1(P_e)] \), that is \( p_1 F^{WO}_1(P_e) \).

When unit 1 fails to perform, its forced outage of \( K_1 = 200 \) MW contributes 200 MW to the equivalent load of 300 MW. Hence, the other probability that the equivalent load \( P_e \geq 300 \) MW (when Unit 1 fails to perform) is the product of the probability that Unit 1 fails \( (q_1) \) and the probability that the equivalent load will exceed \( P_e - K_1 = 300 - 200 = 100 \) MW without the \( K_1 = 200 \) MW allowance for the forced-outage of Unit 1 \( [F^{WO}_1(P_e - K_1)] \); that is, \( q_1 F^{WO}_1(P_e - K_1) \).

Hence, the equivalent load curve with allowance for forced-outages of Unit 1, \( F^W_1(P_e) \), is the sum of the probabilities for states 1 and 2,

\[
F^W_1(P_e) = p_1 F^{WO}_1(P_e) + q_1 F^{WO}_1(P_e - K_1) \quad (3.9)
\]

or

\[
F^W_1(P_e) = 0.7 F^{WO}_1(P_e) + 0.3 F^{WO}_1(P_e - 200) \quad (3.10)
\]

For the \( P_e = 300 \) MW example of Figure 3.3

\[ F^{WO}_1(300) = 0.400 \text{ and } F^{WO}_1(100) = 1.00. \text{ Hence} \]

\[ F^W_1(300) \text{ (point d)} = 0.7 \times 0.400 + 0.3 \times 1.00 = 0.7 \text{, and} \]

\[ F^W_1(100) \text{ (point b)} = 1.00. \text{ Hence} \]
\[ F_{1}^{w}(300) = 0.7 \times (0.4) + 0.3 \times (1.0) = 0.58 \] (point d) (point b) (point g)

Continuing thus for all the points along \( F_{1}^{w} \):

\[ F_{1}^{w}(200) = 0.7 \times 0.600 + 0.3 \times 1.0 = 0.720 \] (point c) (point a) (point f)

\[ F_{1}^{w}(400) = 0.7 \times 0.0 + 0.3 \times 0.600 = 0.180 \] (point e) (point c) (point h)

\[ F_{1}^{w}(500) = 0.7 \times 0.0 + 0.3 \times 0.400 = 0.120 \] (point t) (point d) (point i)

\[ F_{1}^{w}(600) = 0.7 \times 0.0 + 0.3 \times 0.0 = 0.000 \] (point j) (point e) (point j)

In more general terms, any unit \( r \) can be convolved into the equivalent load distribution,

\[ F_{r}^{w}(P_{e}) = P_{r} \cdot F_{r}^{w0}(P_{e}) + q_{r} \cdot F_{r}^{w0}(P_{e} - K_{r}) \]

or

\[ \begin{bmatrix} \text{Prob.}(P>P_{e}) \text{with outages of } r \text{ incl.} \\ \text{with outages of } r \text{ incl.} \end{bmatrix} = \begin{bmatrix} \text{Prob. } \text{r performs} \\ \text{w/o outages} \end{bmatrix} \cdot \begin{bmatrix} \text{Prob.}(P>P_{e}) \text{w/o outages of } r \text{ incl.} \\ \text{w/o outages of } r \text{ incl.} \end{bmatrix} + \begin{bmatrix} \text{Prob. } \text{r fails} \\ \text{w/o outages of } r \text{ included} \end{bmatrix} \]

(3.14)

MW Contribution to Equivalent load:

\[ 0 + \frac{P}{e} \quad \frac{K}{r} + \frac{(P - K_{r})}{e} \]

\[ \frac{P}{e} \quad \frac{P}{e} \]
In deriving Equation (3.13), use was made of the common assumption of statistical independence between the forced-outages of the various units vis-a'-vis each other and the customer demand. Furthermore, Equation (3.13) is valid for all \( P_e \). One limiting case is \( P_e \) less than the minimum load where each \( F^\text{wo}_r = 1 \) as does the resulting \( F^W_r(P_e) \). For very large \( P_e \), each \( F^\text{wo}_r = 0 \) and, likewise, \( F^W_r(P_e) = 0 \).

Equation (3.13) is the heart and soul of the Booth-Baleriaux model. All subsequent calculations involving \( F \), whether convolutions or deconvolutions (see Section 3.3.2.1) are merely rearrangements of it.

Returning to the two unit example, Figure 3.3 indicates the resulting \( F^W_1 \) obtained by applying Equation (3.13) at each multiple of 100 MW. [Equation (3.13) could be applied explicitly at intermediate \( P_e \), but linear interpolation is rigorously correct for this example because the \( F_D \) curve consists of straight-line segments.]

Since Unit 2 follows Unit 1 in the loading order, the production of Unit 2 must be determined using an equivalent load curve (\( F^\text{wo}_2 \)) that includes not only the direct customer load demands, \( F_D \), but also the forced-outages of units to the left of it in the loading order (i.e., Unit 1). Thus,

\[
F^\text{wo}_2(P_e) = F^W_1(P_e)
\]
That is, the probability that the equivalent load will exceed a particular value $P_e$ without taking into account forced-outages of Unit 2 equals the same probability taking into account forced-outages of Unit 1.

As with Unit 1, the loading of Unit 2 is determined by multiplying the total demand on the unit (area sfghits) by its performance probability $p_2$,

$$E_2 = T' p_2 \int_{200}^{500} F_2^{WO}(P_e) dP_e \quad (3.16)$$

$$E_2 = 1 \text{ hour} \times 0.60 \times 118 \text{ MWH} = 70.8 \text{ MWH} \quad (3.17)$$

Rewriting Equation (3.16) in general notation for any Unit $r$,

$$E_r = T' p_r \int_{P_r^o}^{P_r^o+K_r} F_r^{WO}(P_e) dP_e \quad (3.18)$$

where $P_r^o = \text{Loading point for unit } r, \text{ MW}$

Now that Unit 2's production has been accounted for, its outages must be convolved into $F_2^{WO}$. By applying Equation (3.13),

$$F_2^{W}(P_e) = p_2 \cdot F_2^{WO}(P_e) + q_2 \cdot F_2^{WO}(P_e - K_2) \quad (3.19)$$
For example (see Figure 3.3), since $K_2 = 300$ MW and $p_2 = 60\%$,

$$F_2^W(P_e) = 0.6 \times F_2^{WO}(P_e) + 0.4 \times F_2^{WO}(P_e-300) \quad (3.20)$$

In particular, at $P_e = 500$ MW (point n)

$$F_2^W(500) = 0.6 \times 0.120 + 0.4 \times 0.720 = 0.360 \quad (3.21)$$

Continuing thus,

$$F_2^W(600) = 0.6 \times 0.0 + 0.4 \times 0.580 = 0.232 \quad (3.22)$$

$$F_2^W(700) = 0.6 \times 0.0 + 0.4 \times 0.180 = 0.072 \quad (3.23)$$

$$F_2^W(800) = 0.6 \times 0.0 + 0.4 \times 0.120 = 0.048 \quad (3.24)$$

$$F_2^W(900) = 0.6 \times 0.0 + 0.4 \times 0.0 = 0.000 \quad (3.25)$$

Since both of the units on the system have been convolved in via Equation (3.13), the resulting $F_2^W$ equivalent load distribution (see Figure 3.3) includes the entire system, $F_T^W$.

Hence, the remaining $D_U$ unserved energy (i.e., unserved by the $K_T$ MW of the system's own resources or
area from the) is equal to

\[ D_U = T' \int_{K_T}^{\infty} F_T(P_e) dP_e = 53.2 \text{ MWH} \quad (3.23) \]

This energy represents the amount of emergency support required from neighboring utilities.

The second measure of system reliability is the LOLP, loss-of-load probability (i.e., percent of time emergency support is required: \( P_e > K_T \)). Hence,

\[ \text{LOLP} = F_T(P_e = 500 \text{ MW}) = 0.360 \quad (3.24) \]

(point n)

Note that total system production plus emergency purchases have met total customer demand:

\[ D_T = E_1 + E_2 + D_U \quad (3.25) \]

\[ 250 \text{ MWH} = 126 + 70.8 + 53.2 \text{ MWH} \quad (3.26) \]

3.3.1.3 Single Increment Example for Reference Utility System

Returning to the original Reference Utility System of Section 2.1.2.3, the customer loads of Figure 2.9 are repeated in Figure 3.4. As for the five generating units, assume the loading order, unit characteristics and average (i.e., equivalent single increment, see Table C.13 in
Figure 3.4

Loading Order and Energy Cost for Example 4

<table>
<thead>
<tr>
<th>UNIT</th>
<th>RATED CAP. (MW)</th>
<th>PERF. PROB. (%)</th>
<th>ENERGY COST ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>200</td>
<td>95</td>
<td>4.9325</td>
</tr>
<tr>
<td>II</td>
<td>300</td>
<td>90</td>
<td>3.8411</td>
</tr>
<tr>
<td>III</td>
<td>600</td>
<td>90</td>
<td>2.0324</td>
</tr>
<tr>
<td>IV</td>
<td>800</td>
<td>85</td>
<td>1.9125</td>
</tr>
</tbody>
</table>

$T' = 730$ HOURS

$F_D$: DIRECT CUSTOMER LOAD-DURATION

$F_e$: PROBABILITY ($P_e^2$)

$P_e$: EQUIVALENT LOAD (MW)
Appendix C) costs also indicated in Figure 3.4. This then represents Example 4 on the Reference System.

Applying the load-then-convolve sequence of Section 3.3.1.2, the unit loadings $E_r$ are simulated in order. Table 3.1 presents all of the resulting probability distributions.

When the last unit (Unit I) has been convolved in, the resulting $F_I^W$ distribution includes the entire system $F_T^W$. Hence,

$$D_U = T' \int_{K_T}^{\infty} F_T^W(P_e)dP_e = 30,111 \text{ MWH}$$

(3.27)

and

$$\text{LOLP} = F_T^W(P_e = K_T) = 15.647\%$$

(3.28)

This completes the Booth-Baleriaux energy calculations for Example 4. Equation (2.21) can then be utilized to determine the cost of each unit's energy production.

$$X_r = \bar{e}_r \cdot E_r$$

(3.29)

Figure 3.5 sketches the complete flow of calculations, including the energy and cost totals (see also Table 3.2).
### Table 3.1

**Summary of Equivalent Load Distributions for Example 4 with Indication of Segments Used for Loading Each Unit**

<table>
<thead>
<tr>
<th>Unit Loaded, ((r))</th>
<th>(V)</th>
<th>III</th>
<th>IV</th>
<th>II</th>
<th>I</th>
<th>Neigh. Util.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Cap., ((K_r))</td>
<td>800MW</td>
<td>300</td>
<td>600</td>
<td>200</td>
<td>100</td>
<td>(\infty)</td>
</tr>
<tr>
<td>Perf. Prob. ((P_r))</td>
<td>0.85</td>
<td>0.90</td>
<td>0.90</td>
<td>0.95</td>
<td>0.95</td>
<td>1.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(P_e) (MW)</th>
<th>(F_D)</th>
<th>(F_V)</th>
<th>(F_{III})</th>
<th>(F_{IV})</th>
<th>(F_{II})</th>
<th>(F_I)</th>
<th>(F_T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>900</td>
<td>.95</td>
<td>.9575</td>
<td>.96175</td>
<td>.96558</td>
<td>.96730</td>
<td>.96893</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>.90</td>
<td>.9150</td>
<td>.92350</td>
<td>.93115</td>
<td>.93459</td>
<td>.93623</td>
<td></td>
</tr>
<tr>
<td>1100</td>
<td>.85</td>
<td>.8725</td>
<td>.88525</td>
<td>.89672</td>
<td>.90017</td>
<td>.90189</td>
<td></td>
</tr>
<tr>
<td>1200</td>
<td>.80</td>
<td>.8300</td>
<td>.84275</td>
<td>.85848</td>
<td>.86211</td>
<td>.86401</td>
<td></td>
</tr>
<tr>
<td>1300</td>
<td>.50</td>
<td>.5750</td>
<td>.60900</td>
<td>.64810</td>
<td>.66053</td>
<td>.67061</td>
<td></td>
</tr>
<tr>
<td>1400</td>
<td>.20</td>
<td>.3200</td>
<td>.37525</td>
<td>.43772</td>
<td>.45876</td>
<td>.46885</td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td>.15</td>
<td>.2775</td>
<td>.33275</td>
<td>.39565</td>
<td>.40827</td>
<td>.41080</td>
<td></td>
</tr>
<tr>
<td>1600</td>
<td>.10</td>
<td>.2350</td>
<td>.26900</td>
<td>.33445</td>
<td>.33961</td>
<td>.34305</td>
<td></td>
</tr>
<tr>
<td>1700</td>
<td>.05</td>
<td>.1850</td>
<td>.19850</td>
<td>.26718</td>
<td>.27360</td>
<td>.27690</td>
<td></td>
</tr>
<tr>
<td>1800</td>
<td>.00</td>
<td>.1350</td>
<td>.14925</td>
<td>.21860</td>
<td>.22439</td>
<td>.22685</td>
<td></td>
</tr>
<tr>
<td>$P_e$ (MW)</td>
<td>$F_D$</td>
<td>$F_V$</td>
<td>$F_{VIII}$</td>
<td>$F_{IV}$</td>
<td>$F_{II}$</td>
<td>$F_I$</td>
<td>$F_T$</td>
</tr>
<tr>
<td>-----------</td>
<td>------</td>
<td>------</td>
<td>-----------</td>
<td>---------</td>
<td>---------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>1900</td>
<td>.1275*</td>
<td>.13825</td>
<td>.18532</td>
<td>.18942</td>
<td>.19117</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>.1200</td>
<td>.12650</td>
<td>.15138</td>
<td>.15474</td>
<td>.15647</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2100</td>
<td>.0750</td>
<td>.08100</td>
<td>.10618</td>
<td>.11013</td>
<td>.11236</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2200</td>
<td>.0300*</td>
<td>.03975</td>
<td>.06268</td>
<td>.06711</td>
<td>.06926</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2300</td>
<td>.0225</td>
<td>.03225</td>
<td>.04888</td>
<td>.05174</td>
<td>.05251</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2400</td>
<td>.0150</td>
<td>.02100</td>
<td>.03382</td>
<td>.03527</td>
<td>.03609</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td>.0075</td>
<td>.00975</td>
<td>.02260</td>
<td>.02391</td>
<td>.02448</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2600</td>
<td>.0000</td>
<td>.00225</td>
<td>.01468</td>
<td>.01563</td>
<td>.01605</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2700</td>
<td>.00150</td>
<td>.00945</td>
<td>.01011</td>
<td>.01038</td>
<td>.01038</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2800</td>
<td>.00075</td>
<td>.00465</td>
<td>.00515</td>
<td>.00540</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Example: $0.03975 = (0.9) (0.0300) + (0.1) (0.1275)$
Calculational Steps for Example 4

UNIT V
CONVOLVE

\[ F_D = F_{WO} \]

Eq. (3.18)

\[ E \quad \text{(GWH)} \]

496.40

\[ \bar{e_r} \quad \text{(10^3$)} \]

\[ \$/\text{MWh} \]

949.4

(Figure 3.4)

UNIT IV
LOAD
CONVOLVE

\[ F_W = F_{WO} \]

184.54

\[ \$/\text{MWh} \]

375.0

UNIT III
LOAD
CONVOLVE

\[ F_W = F_{WO} \]

195.17

\[ \$/\text{MWh} \]

710.6

UNIT II
LOAD
CONVOLVE

\[ F_W = F_{WO} \]

30.85

\[ \$/\text{MWh} \]

152.2

UNIT I
LOAD
CONVOLVE

\[ F_W = F_{WO} \]

11.93

\[ \$/\text{MWh} \]

193.3

LOAD
CONVOLVE

\[ F_W = F_{WO} \]

30.11

\[ \$/\text{MWh} \]

301.1

TOTALS

949.00

2681.6

Figure 3.5
TABLE 3.2

Example 4 on Reference Utility System:
"Single Increment Booth-Baleriaux Model"

(See Appendix C for further details.)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Increment</th>
<th>Position in Loading Order</th>
<th>Increment Energy $E_{ri}$ (GWH)</th>
<th>Increment Cost $X_{ri}$ ($10^3$ $$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>5</td>
<td>11.93</td>
<td>193.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>4</td>
<td>30.85</td>
<td>152.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>1</td>
<td>2</td>
<td>184.54</td>
<td>375.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>1</td>
<td>3</td>
<td>195.17</td>
<td>710.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>1</td>
<td>1</td>
<td>496.40</td>
<td>949.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Utility Production

|                     | 918.89 | 2380.5 |

Emergency Purchases ($10 $/MWH)

|                     | 30.11  | 301.1  |

Total

|                     | 949.00 | 2681.6 |

Loss-of-load Probability, LOLP = 15.6%
3.3.1.4 Single Increment Algorithm

From Figure 3.5, the load-convolve sequence of the single increment Booth-Baleriaux algorithm can be stated as follows:

**Step 1:** From the specified loading order, label the first unit as unit $r$. Re-label $F_D$, the normalized customer load-duration curve so that it becomes the "current" $F$.

**Step 2:** Re-label the current $F$ so that it becomes $F_{w0}^r$.

**Step 3:** Load unit $r$ by calculating its expected production,

$$E_r = T' \int_{P_r^o}^{P_r^o+K_r} F_{w0}^r(P_e) dP_e$$  

where $P_r^o = \text{equivalent load level when unit } r \text{ is at zero power level}$.

**Step 4:** Convolve the unit's outages into $F_{w0}^r$ to account for the production unit $r$ was unable to satisfy,

$$F_w^r(P_e) = P_r \cdot F_{w0}^r(P_e) + q_r \cdot F_{w0}^r(P_e - K_r)$$  

**Step 5:** If there are no more units in the loading order, go to **Step 6**. Otherwise, label the next unit in the specified loading order as
unit r. Return to Step 2 and continue.

**Step 6:** Since there are no more units to be loaded, the current $F$ is for the total system. Label it $F_T$. Then,

$$\text{LOLP} = F_T(P_e = K'_T) \tag{3.32}$$

and

$$D_u = T' \int_{K'_T}^{\infty} F_T(P_e) dP_e \tag{3.33}$$

This completes the Booth-Baleriaux algorithm for one-piece units. Production costing of the energy,

$$X_r = \bar{e}_r E_r \tag{3.34}$$

can be performed either on-line as a second part of Step 3 or off-line after all of the energies have been assigned.

### 3.3.1.5 Important Numerical Properties

Seven important numerical properties of the Booth-Baleriaux model are worthy of note. The first three relate directly to the computational effort involved while the latter four deal with the more philosophical aspects of the results.
First, by invoking Equation (3.6), the time involved in the convolution of Equation (3.31) can be reduced by almost one-half by rearranging to:

\[
F^w_r(P_e) = F^w_r(P_e) + q_r [F^wo_r(P_e - K_r) - F^wo_r(P_e)]
\]  (3.35)

Two time-consuming multiplications can be reduced to one. [As a sidelight, \(F^w_r\) at \(P_e\) never decreases in magnitude as loading proceeds since the second term in Equation (3.35) can never by negative.] Secondly, though Example 4 involved six different \(F\)'s, only one was required at any one time and, furthermore, none was ever required a second time; the result being that only one array of storage need ever be allocated to \(F\). The array \(F\) is stored in the computer as a one dimensional array of equally-spaced points \(DM \times MW\) apart (see Figure 3.6). Thus the 12th array location has stored in it \(F(P_e = 12 \times DM)\). Linear interpolation is assumed between points.

Since the convolution of Equation (3.31) involves only the point of interest (at \(P_e\)) and points to its left (specifically, at \(P_e - K_r\)), it is convenient to begin the convolution of each unit \(r\) at the extreme right-hand side of Figure 3.6. Proceeding toward the left, each array location has its current quantity \([F^wo_r(P_e)]\) increased by \(q_r \times [F^wo_r(P_e - K_r) - F^wo_r(P_e)]\) per Equation (3.35). In this manner, \(F^wo_r\) is convoluted to yield \(F^w_r\). By being identically located, \(F^w_r\) automatically becomes \(F^wo_r\) for the next unit. The result is that the single \(F\) array is kept "current" as the scheduling algorithm...
Figure 3.6

Computer Representation of Equivalent Load Curve

- $F_r$: Probability ($P_e \geq$)
- $P_e$: Equivalent Load (MW)
proceeds from unit to unit.

The third and final point concerning computational details involves deconvolution. Even if a previous $F$ were needed again, it could be easily restored by reversing Equation (3.31). Such a deconvolving, or stripping out, of the outages of a previously included unit $r$ can thus be achieved by,

$$F_r^{WO}(P_e) = \frac{1}{P_r} [F_r^w(P_e) - q_r \cdot F_r^{WO}(P_e - K_r)]$$  \hspace{1cm} (3.36)

For deconvolution, the direction of calculation would also be reversed, proceeding from left to right of Figure 3.6 so that $F(P_e)$ for $P_e$ to the left of the point of interest would already be $F^{WO}$ as required by Equation (3.36).

The first important philosophical result has already been seen in Section 3.3.1.2: The production of previous increments is unaffected by changes in the loading order of subsequent units. The order of the computations bears this out immediately.

Secondly, with regard to any currently stored $F$ array, it is a function of the units convolved in, but not a function of the order in which they were added. Consider an initial customer demand $F_D$ and the simple two unit utility system (Unit 1 and Unit 2). The task is to prove that $F_T(P_e)$ is identical whether the loading order is (1) Unit 1, then Unit 2 (see Section 3.3.1.2) or (2) Unit 2, then
Unit 1.

Equation (2.31) holds for both cases,

\[ F^W_1(P_e) = p_1 F^WO_1(P_e) + q_1 F^WO_1(P_e - K_1) \]  \hspace{1cm} (3.37)

and

\[ F^W_2(P_e) = p_2 F^WO_2(P_e) + q_2 F^WO_2(P_e - K_2) \]  \hspace{1cm} (3.38)

For Case (1) (Unit 1, then Unit 2),

\[ F^WO_1 = F_D \]  \hspace{1cm} (3.39)

\[ F^WO_2 = F^W_1 \]  \hspace{1cm} (3.40)

and

\[ F_T = F^W_2 \]  \hspace{1cm} (3.41)

Thus,

\[ F_T(P_e) = p_2 \left[ p_1 F_D(P_e) + q_1 F_D(P_e - K_1) \right] \]

\[ + q_2 \left[ p_1 F_D(P_e - K_2) + q_1 F_D(P_e - K_2 - K_1) \right] \]  \hspace{1cm} (3.42)

or finally,

\[ F_T(P_e) = p_1 p_2 F_D(P_e) + q_1 p_2 F_D(P_e - K_1) \]

\[ + p_1 q_2 F_D(P_e - K_2) + q_1 q_2 F_D(P_e - K_1 - K_2) \]  \hspace{1cm} (3.43)
For Case (2) (Unit 2, then Unit 1),

\[ F_{WO}^{2} = F_{D} \quad (3.44) \]

\[ F_{WO}^{1} = F_{D}^{2} \quad (3.45) \]

and

\[ F_{T} = F_{D}^{1} \quad (3.46) \]

Thus,

\[ F_{T}(P_{e}) = p_{1} [p_{2}F_{D}(P_{e}) + q_{2}F_{D}(P_{e} - K_{2})] \]

\[ + q_{1} [p_{2}F_{D}(P_{e} - K_{1}) + q_{2}F_{D}(P_{e} - K_{1} - K_{2})] \]

(3.47)

or, rearranging,

\[ F_{T}(P_{e}) = p_{1}p_{2}F_{D}(P_{e}) + q_{1}p_{2}F_{D}(P_{e} - K_{1}) \]

\[ + p_{1}q_{2}F_{D}(P_{e} - K_{2}) + q_{1}q_{2}F_{D}(P_{e} - K_{1} - K_{2}) \]

(3.48)

Since \( F_{T} \) in Case (1) [Equation (3.43)] is term by term identical with \( F_{T} \) in Case (2) [Equation (3.48)], the proof for the two unit system is complete. The generalization to more units is straightforward, though cumbersome and is not presented formally. In conclusion, each \( F \) is a function of the units whose outages have already been included but not a
function of their order of inclusion.

The third philosophical point follows immediately from the above. Since F is independent of the order of inclusion, a unit's loading, determined using the F, is also independent of the ordering. However, as with F, it does depend on which units are included.

The fourth and final philosophical point also follows from the second. When all units have been convolved in, the resulting \( F_T \) is independent of the loading order. Thus, the LOLP and \( D_U \) are not functions of the startup and loading order, but only of the original customer demand and the aggregate system equipment not on scheduled maintenance.

3.3.2 Modifications for Multiple Increments

3.3.2.1 Algorithm Derived

The original single increment Booth-Baleriaux model was a tremendous leap forward in utility system simulation. As Example 3 in Section 2.2.1 pointed out, not only was the production of peaking equipment more accurately predicted, but the model was also better able to estimate the LOLP and unserved energy \( D_U \) by the same technique. One large stumbling block remained--how to accurately represent the interweaving of the multiple increments of the various units. Units are not scheduled as single blocks of capacity, not only because of economics, but also because of spinning reserve requirements.
To handle this more general case rigorously, only a slight modification of the single increment algorithm is required. The load-convolve pattern is replaced with a deconvolve-load-convolve sequence.

To derive the algorithm, after loading the first increments of several units, assume (1) the next increment in the loading order is \( \Delta K_{ri} \) (the \( i \) th increment of unit \( r \)), (2) that \( i > 1 \) and (3) that the current \( F_r, (F_{r,i-1}^w) \) already includes unit \( r \)'s increments up to \( K_{r,i-1} \). If \( \Delta K_{ri} \) was mistakenly loaded using \( F_{r,i-1}^w \) itself, the \( i \) th increment would, in essence, be meeting demands due to (1) customers, (2) the forced-outages of increments of other units already loaded and (3) the forced-outages of its own lower (\( i-1 \)) increments. However, the latter is an impossibility. If the lower increments are down on forced-outage, so is \( \Delta K_{ri} \). (The converse is not necessarily true. See Appendix A.)

Thus, to load \( \Delta K_{ri} \) properly (see Figure 3.7), the previously convolved forced-outages of unit \( r \) (\( K_{r,i-1}^w \text{ MW at } p_r \text{ percent} \)) must be stripped out of \( F \) to yield \( F_{r,i-1}^{WO} \).

Equation (3.36) does just that,

\[
F_{r,i-1}^{WO}(P_e) = \frac{1}{p_r} \left[ F_{r,i-1}^w(P_e) - \epsilon_r F_{r,i-1}^{WO}(P_e - K_{r,i-1}) \right]
\]
Deconvolve-Load-Convolve Scheme for Multiple Increments

STEP 1
DECONVOLVE EQ. (3.49)

STEP 2
LOAD EQ. (3.51)

STEP 3
CONVOLVE EQ. (3.52)

$P_{ri}$

$F_{r,i-l}$

$F_{wo}$

$F_{r,i-l} = F_{wo}$

$P_e$, EQUIVALENT LOAD (MW)

$F_e$, PROBABILITY ($P_e \geq$)

$P_e$, EQUIVALENT LOAD (MW)

Figure 3.7
After deconvolution,

\[ F_{wi,i-1}^{wo} = F_{ri}^{wo} \]  

(3.50)

and

\[ E_{ri} = T' \int_{P_{ri}}^{P_{ri} + \Delta K_{ri}} F_{ri}^{wo}(P_e) dP_e \]  

(3.51)

Once the i th increment itself has been loaded, the outages of all the i increments can be convolved into \( F_{ri}^{wo} \) at one time,

\[ F_{ri}^{w}(P_e) = P_r \cdot F_{ri}^{wo}(P_e) + q_r \cdot F_{ri}^{wo}(P_e - K_{ri}) \]  

(3.52)

The resulting deconvolve-load-convolve sequence of Figure 3.7 can be applied successively to each increment in the loading order.

Using the indicated multiple increment loading order (Units III-V must run; 80 MW spinning reserve), Table 3.3 presents the results for this Example 5 on the Reference Utility System. Table 3.4 presents a summary comparison of Examples 1 through 5. The \( D_T \), \( D_U \) and LOLP are reassuringly equal for all three probabilistic examples. Furthermore, the multiple increment Example 5 does save $123,000 in production costs over the less economical (early startup
Example 5 on Reference Utility System:
"Multiple Increment Booth-Baleriaux Model (V-2, then III-2)"

(Among Nuclear Upper Increments V-2, then III-2)
(See Appendix C for further details.)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Increment</th>
<th>Position in Loading Order</th>
<th>Increment Energy $E_{ri}$ (GWH)</th>
<th>Increment Cost $X_{ri}$ $(10^3$ $$$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>9</td>
<td>11.93</td>
<td>193.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
<td>14.01</td>
<td>59.5</td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>6</td>
<td>36.71</td>
<td>201.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
<td>14.01</td>
<td>59.5</td>
</tr>
<tr>
<td>III</td>
<td>1</td>
<td>2</td>
<td>65.70</td>
<td>149.8</td>
</tr>
<tr>
<td>(Nuclear)</td>
<td>2</td>
<td>5</td>
<td>103.90</td>
<td>197.4</td>
</tr>
<tr>
<td>IV</td>
<td>1</td>
<td>3</td>
<td>131.40</td>
<td>515.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7</td>
<td>70.85</td>
<td>235.2</td>
</tr>
<tr>
<td>V</td>
<td>1</td>
<td>1</td>
<td>186.15</td>
<td>418.8</td>
</tr>
<tr>
<td>(Nuclear)</td>
<td>2</td>
<td>4</td>
<td>298.24</td>
<td>510.0</td>
</tr>
</tbody>
</table>

Utility Production 918.89 2481.0
Emergency Purchases (10 $$/MWH) 30.11 301.1

Total 949.00 2782.1

Loss-of-load Probability, LOLP = 15.6%
<table>
<thead>
<tr>
<th>Example</th>
<th>Remarks</th>
<th>$D_T$ (GWH)</th>
<th>$D_U$ (GWH)</th>
<th>System Production Fuel Cost ($10^6$ $$$)</th>
<th>LOLP (%)</th>
<th>Reference Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Deterministic (No Forced Outages)</td>
<td>949</td>
<td>0.00</td>
<td>2.443</td>
<td>0.00</td>
<td>2.3</td>
</tr>
<tr>
<td>2</td>
<td>Deterministic (with Reduced Capacities)</td>
<td>949</td>
<td>0.11</td>
<td>2.514</td>
<td>1.25</td>
<td>2.4</td>
</tr>
<tr>
<td>3</td>
<td>Probabilistic, Multiple Increment; Early Startup of II</td>
<td>949</td>
<td>30.11</td>
<td>2.604</td>
<td>15.65</td>
<td>2.5</td>
</tr>
<tr>
<td>4</td>
<td>Probabilistic, Single Increment; No Must-Run, No Spin Res.</td>
<td>949</td>
<td>30.11</td>
<td>2.380&lt;sup&gt;1&lt;/sup&gt;</td>
<td>15.65</td>
<td>3.2</td>
</tr>
<tr>
<td>5</td>
<td>Probabilistic, Multiple Increment; Operating Constraints App'd. to Econ. order</td>
<td>949</td>
<td>30.11</td>
<td>2.481&lt;sup&gt;2&lt;/sup&gt;</td>
<td>15.65</td>
<td>3.3</td>
</tr>
</tbody>
</table>

<sup>1</sup>Lower limit if all operating constraints are violated.

<sup>2</sup>Lower limit if all operating constraints are satisfied.
of Unit II) but practical (spinning reserve satisfied) multiple increment Example 3. The low cost of Example 4 is misleading because the must-run status of Unit IV and the system spinning reserve requirement were ignored, rendering the single increment loading order infeasible (i.e., the system operating constraints were violated).

Before formally stating the steps of the more general multiple increment Booth-Baleriaux algorithm in the next section, two important points need to be made to justify that generality. First, the method is valid even if \( i = 1 \). For then,

\[
K_{r,i-1} = K_{r,0} = 0
\]  

(3.53)

and the deconvolution of Equation (3.49) reduces to

\[
F_{r0}^{WO}(P_e) = \frac{1}{P_r} \left[ F_{r0}^W(P_e) - q_r F_{r0}^{WO}(P_e - 0) \right]
\]  

(3.54)

Utilizing Equation (3.6), \( F_{r0}^{WO} = F_{r0}^W \). That is, if no increments of the unit have been previously loaded, straightforward application of Equation (3.49) correctly deconvolves zero MW.

The second point also involves a limiting condition. Suppose all the multiple increments for a given unit happen to be scheduled adjacent to each other. This case ought to revert to the results of the single increment model. Indeed, each "convolution to left; deconvolution to the right"
sequence returns F to the identical $F_{r}^{WO}$. In fact, this was the actual scheme used to calculate Example 4 of Section 3.3.1.3 (see Appendix C).

### 3.3.2.2 Multiple Increment Algorithm

The deconvolve-load-convolve sequence of the more general, multiple increment Booth-Baleriaux algorithm is stated as follows:

**Step 1:** From the specified loading order, label the first unit increment as unit $r$, increment $i$ ($i = 1$). Re-label $F_D$ the normalized customer load-duration curve so that it becomes $F_{r,i-1}^W$.

**Step 2:** Deconvolve the $i-1$ previously loaded increments of unit $r$ which cannot create indirect demand on the current increment,

$$
F_{r,i-1}^{WO}(P_e) = \frac{1}{P_r} \left[ F_{r,i-1}^W(P_e) - q_r F_{r,i-1}^{WO}(P_e - K_{r,i-1}) \right]
$$

(3.55)

and re-label the result $F_{ri}^{WO}$.

**Step 3:** Load the unit increment by calculating its expected production,

$$
E_{ri} = T' \int_{P_{ri}}^{P_{ri} + \Delta K_{ri}} F_{ri}^{WO}(P_e) dP_e
$$

(3.56)
where \( P_{ri}^* \) = equivalent load level when the unit increment is at zero power level.

**Step 4:** Convolve the outages of the unit's increments loaded thus far \( (K_{ri}) \) into \( F_{ri}^{WO} \) to account for the production unit \( r \) has thus far been unable to satisfy,

\[
F_{ri}^W(P_e) = P_r \cdot F_{ri}^{WO}(P_e) + q_r \cdot F_{ri}^{WO}(P_e - K_{ri}) \quad (3.57)
\]

**Step 5:** If there are no more unit increments, go to **Step 6**. Otherwise, label the next unit increment in the specified loading order as unit \( r \), increment \( i \). Re-label the current \( F \) so that it becomes \( F_{r,i-1}^W \). Return to **Step 2** and continue.

**Step 6:** Since there are no more increments to be loaded, the current \( F \) is for the total system. Label it \( F_T \). Then,

\[
\text{LOLP} = F_T(P_e = K'_T) \quad (3.58)
\]

and

\[
D_U = T' \int_{K'_T}^{\infty} F_T(P_e) dP_e \quad (3.59)
\]

This completes the Booth-Baleriaux multiple increment algorithm. Comparing it with the single increment
algorithm of Section 3.3.1.4, only Step 2 is significantly different. Instead of immediately re-labeling the current $F$ to $F^WO_r$, a deconvolution must first be performed to ensure that no outages of unit $r$ are included.

As before, production costing of the energy increment,

$$x_{rl} = \bar{e}_{rl} E_{rl}, \text{ or } x_{ri} = \lambda_{ri} E_{ri} \text{ for } i > 1 \quad (3.60)$$

can be performed either on-line as a second part of Step 3 or off-line after all of the energies have been assigned.

3.3.3 Constancy of Nuclear Potential

An extremely important conclusion regarding nuclear energy production can be deduced by combining the simple logic of the optimized loading order presented in Sections 2.4.3 and 3.2 and the purely mathematical properties of the Booth-Baleriaux model as discussed in Section 3.3.1.5.

Conclusion: Irrespective of the intra-group loading order of the nuclear increments, the period's nuclear potential $N_P$ is a constant.

Consider Figure 3.8 which presents a typical period load-duration curve being satisfied by a nuclear utility system using a loading order as suggested in Section 3.2. Proceeding from left to right through the startup and loading order, the first two groups of increments are the nuclear minimums (group 1) and the fossil minimums (group 2) for the
Figure 3.8

Loading Order Sub-Groups

\[ F_D \]

\[ K_T = \text{INSTALLED CAPACITY} \]

\( F_e, \text{ LOAD (MW)} \)

1.0

0.5

0.0

GROUP 1

GROUP 2

GROUP 3

GROUP 4

GROUP 5

NUCLEAR MINIMUMS

FOSSIL MUST-RUN MINIMUMS

NUCLEAR UPPER INCREMENTS

REMAINING FOSSIL

EMERGENCY SUPPORT FROM NEIGHBORING UTILITIES
must-run units. Since today's nuclear units all possess incremental costs on the order 0.9 to 1.5 $/MWH, next comes an amorphous block of capacity comprised of all the nuclear upper increments (group 3). (It is assumed that there are units in group 2. Otherwise, groups 3 and 4 must be mixed in order to provide spinning reserve.) After group 3 comes the well-ordered, but much more expensive, remaining fossil equipment (group 4) costing from 2 $/MWH on up. Beyond this installed capacity, are the emergency resources of neighboring utilities (group 5).

The conclusion is postulated as follows:

Given two alternative loading orders for group 3 ($g = 3A$ and $g = 3B$), show that the nuclear potentials are equal:

$$N_{g=3A} = N_{g=3B} \quad (3.61)$$

The other group loading orders remain the same. For instance,

$$g = 4A \equiv 4B \quad (3.62)$$

Since,

$$N \equiv E_g = 1 + E_g = 3 \quad (3.63)$$

The question becomes,

$$E_{g=1A} + E_{g=3A} \neq E_{g=1B} + E_{g=3B} \quad (3.64)$$
Since groups 1 and 2 remain the same and precede group 3, the conclusions of Section 3.3.1.5 dictate that those groups produce the same energy. Dropping the "g =" notation for convenience,

\[ E_{1A} = E_{1B} \]  \hspace{1cm} (3.65)

and

\[ E_{2A} = E_{2B} \]  \hspace{1cm} (3.66)

Moving through group 3, the first increment of group 4 is loaded utilizing the F curve remaining after the last nuclear increment has been convolved in. Since all of the nuclear increments have been convolved in, the current F must be identical for the two alternatives since the order they were included is immaterial. Thus, all of the Booth-Baleriaux calculations for group 4 will be identical and,

\[ E_{4A} = E_{4B} \]  \hspace{1cm} (3.67)

As for DU (\( \equiv E_{g=5} \)), Section 3.3.1.5 already stated that it is invariant. Thus,

\[ E_{5A} = E_{5B} \]  \hspace{1cm} (3.68)

Since the same customer demand is satisfied for both alternatives,
\[ D_T = E_{1A} + E_{2A} + E_{3A} + E_{4A} + E_{5A} \]

\[ D_T = E_{1B} + E_{2B} + E_{3B} + E_{4B} + E_{5B} \]

With four of the five components on the right-hand side being equal, the remaining components must also be equal,

\[ E_{3A} = E_{3B} \]

and Equation (3.64) is, in fact, true.

Therefore,

\[ E_{g=1} + E_{g=3} = N = \text{constant} \]

independent of the intra-nuclear loading order.

Q.E.D.

As a matter of fact, a much more general conclusion can be proven in an analogous manner: Each sub-group of unit increments produces the same energy regardless of the intra-group loading orders, provided that the inter-group loading order remains the same.

Example 6 on the Reference System is presented in Table 3.5. It involves the rearrangement of nuclear upper increments V-2 and III-2 with respect to Example 5 of Table 3.3. In both examples, the two upper nuclear increments produced a total of 402.14 GWH and a system nuclear potential of 653.99 GWH.
Example 6 on Reference Utility System:

"Multiple Increment Booth-Baleriaux Model (III-2, then V-2)"

(Among Nuclear Upper Increments III-2, then V-2)

(See Appendix C for further details.)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Increment</th>
<th>Position in Loading Order</th>
<th>Increment Energy</th>
<th>Increment Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>1</td>
<td>9</td>
<td>11.93</td>
<td>193.3</td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>6</td>
<td>36.71</td>
<td>201.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
<td>14.01</td>
<td>59.5</td>
</tr>
<tr>
<td>III</td>
<td>1</td>
<td>2</td>
<td>65.70</td>
<td>149.8</td>
</tr>
<tr>
<td>(Nuclear)</td>
<td>2</td>
<td>4</td>
<td>131.40</td>
<td>249.7</td>
</tr>
<tr>
<td>IV</td>
<td>1</td>
<td>3</td>
<td>131.40</td>
<td>515.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7</td>
<td>70.85</td>
<td>235.2</td>
</tr>
<tr>
<td>V</td>
<td>1</td>
<td>1</td>
<td>186.15</td>
<td>418.8</td>
</tr>
<tr>
<td>(Nuclear)</td>
<td>2</td>
<td>5</td>
<td>270.74</td>
<td>463.0</td>
</tr>
<tr>
<td>Utility Production</td>
<td>918.89</td>
<td>2486.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergency Purchases (10 $/MWH)</td>
<td>30.11</td>
<td>301.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>949.00</td>
<td>2787.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Loss-of-load Probability, LOLP = 15.6%
The conclusion concerning constant nuclear potential is extremely important to the structure of the nuclear power management model of Figure 2.21 because the Booth-Baleriaux simulation in the SIM does not require detailed reactor-by-reactor nuclear incremental costs. (Recall that "ballpark" nuclear incremental costs were, nonetheless, useful in establishing the loading order groups.) Any intra-nuclear order is as good as any other for calculating the system nuclear potential. The model merely picks an arbitrary order for the amorphous nuclear group (g=3), simulates the system and totals the nuclear production to get the constant nuclear potential.

Furthermore, after all periods have been simulated by the SIM, the SOM begins optimizing the intra-nuclear production of the nuclear potentials. Since period nuclear potential is a constant regardless of the various detailed incremental costs (i.e., loading orders) calculated at each iteration by the CORSOM's (see Section 2.5), the iterations in Figure 2.21 need not loop back through the SIM. All of the above, make this an extremely important conclusion.

3.4 Estimating Startup-Shutdown Cost

To accurately calculate the startup-shutdown cost component of operating revenue requirements, an hour-by-hour production scheduling model is required. Having sacrificed the detailed chronological load shapes for the
more convenient load-duration curves (see Section 2.1.1) covering much longer periods of time, it becomes necessary to estimate startup-shutdown costs by an approximate technique.

Consider Figure 3.9 (after (18)) which displays qualitatively the approximate relation between \( \Omega \), the frequency of startup-shutdowns (per day) and \( L'_{rl} \), the availability-based capacity factor for the unit's first increment. That is,

\[
L'_{rl} = \frac{1}{K_{rl}} \int_{P_{rl}^0}^{P_{rl}^0 + K_{rl}} F_{rl}(P_e) dP_e \tag{3.72}
\]

For must-run units, \( L'_{rl} \) equals 1 and \( \Omega \) equals 0. For very expensive peaking units, \( L'_{rl} \) approaches 0 and \( \Omega \) again approaches 0. As expected, units never shutdown and units never started-up incur no startup-shutdown cost. In between are those units started-up and shutdown on a daily basis and, hence, \( \Omega \) approaches one.

Since unit startup-shutdown cost \( Q_r \) is specified in time independent units of equivalent thermal energy input, multiplying it by \( \varphi_r \), unit thermal energy cost for the time period, permits escalation in terms of undiscounted dollars. Since \( L'_{rl} \) is easily extracted for each unit during the Booth-Baleriaux simulation, the fractional starts per
Example of Startup-Shutdown Frequency versus Availability-Based Capacity Factor [After (18)]
day are easily estimated given the proper dependence of $\Omega$ upon $L'_{rl}$. Thus, a period $T'/24$ days long, incurs total startup-shutdown cost amounting to

$$X_s = \frac{T'}{24} R \sum_{r} Q_r \Omega(L'_{rl}) \quad (3.73)$$

Table 3.6 presents the detailed calculation of unit startup-shutdown costs for Example 5 which was presented in Table 3.3.

3.5 Determining Cost of Emergency Purchases

The determination of expenditures relative to $D_U$ emergency electricity purchases from neighboring utilities is straight-forward once the SIM has been given an $\bar{e}_U$ average cost for this emergency support. The total expenditure is merely,

$$X_U = \bar{e}_U \cdot D_U \quad (3.74)$$

3.6 SYSINT, A Computerized Version of the SYStem INTergration Model

SYSINT, a 2000 card Fortran IV version of the SYStem INTergration Model is detailed in Appendix E. This section merely summarizes its capabilities.

The standard two-state forced-outage model (performs or fails) is employed. A single startup frequency curve $\Omega(L'_{rl})$ is input for the entire horizon. The limitations of the current version, though easily altered, are as follows:
### Table 3.6
Calculation of Startup-Shutdown Costs for Example 5 on Reference Utility System

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>90</td>
<td>50</td>
<td>.172</td>
<td>.152</td>
<td>45</td>
<td>6.85</td>
<td>208</td>
</tr>
<tr>
<td>II</td>
<td>50</td>
<td>800</td>
<td>.529</td>
<td>.860</td>
<td>400</td>
<td>344.00</td>
<td>10,460</td>
</tr>
<tr>
<td>III</td>
<td>19</td>
<td>1200</td>
<td>1.000</td>
<td>-0-</td>
<td>228</td>
<td>-0-</td>
<td>-0-</td>
</tr>
<tr>
<td>IV</td>
<td>40</td>
<td>3600</td>
<td>1.000</td>
<td>-0-</td>
<td>1440</td>
<td>-0-</td>
<td>-0-</td>
</tr>
<tr>
<td>V</td>
<td>18</td>
<td>2400</td>
<td>1.000</td>
<td>-0-</td>
<td>432</td>
<td>-0-</td>
<td>-0-</td>
</tr>
</tbody>
</table>

Total Startup-Shutdown Cost-$12,670

1 See Figure 3.9
(1) up to 100 units (including retirements and additions),
(2) up to 5 valve points for each unit,
(3) no limit on number of strategies per computer run
(4) up to 100 time periods per strategy and
(5) up to 25 typical load-duration "shapes",
    stored in completely normalized form (i.e., peak demand also equals one).

The multi-period strategy is input for each unit in the following form:

(1) the period installed,
(2) period just prior to retirement and
(3) up to 20 intermediate periods of downtime for maintenance or refueling.

For each period the following data may be input or altered:

(1) Choice of load-duration shape,
(2) Forecasted peak demand,
(3) Expected spinning reserve requirement,
(4) Length of time period,
(5) Average cost of emergency purchase energy,
(6) Fuel cost for each unit (optional initial guess for nuclear units),
(7) Performance probability for each unit and
(8) Startup order indicating must-run units and peaking equipment.
As for typical running time, each period of a simulation of a utility system containing 40 units with a total of 150 valve points requires approximately 2.5 CPU sec on an IBM 370 model 155 computer in an MVT environment. The code itself requires 108 K bytes of storage, i.e., not including the computer system supervisor. Total core requirements are thus approximately 134 K bytes.

Data transfer from SYSINT to SYSOPT (see Section 4.6 and Appendix F) is completely automated via either disk, magnetic tape or punched cards.

3.7 Summary of the SIM

For each multi-year refueling and maintenance strategy, the SIM performs period-by-period detailed production scheduling utilizing the Booth-Baleriaux probabilistic utility system model. Besides, calculating the system nuclear potential \( N \) (shown to be a constant), the model outputs the following system cost components:

1. \( X_F \), the fossil fuel expense related to electricity production,
2. \( X_S \), the startup-shutdown cost and
3. \( X_U \), the cost of emergency energy purchases.

This and other data are then passed to the SOM of Chapter 4 for iterative optimization of the production of the nuclear potential and present-valuing of all the cost components to obtain the final ORR for the given strategy.
4.1 Overview of the SOM

The System Optimization Model (SOM), shown schematically in Figure 2.22 performs two tasks for each of the possible alternative refueling and maintenance strategies under investigation. The first, and most difficult, is optimizing each reactor's energy output so as to produce the required system nuclear potential for each period with a minimum total revenue requirement for nuclear fuel over the multi-year horizon (see Section 4.2.1). The SOM receives, as input, the period-by-period results (see Section 3.7) of the System Integration Model (SIM) which are used to formulate the constraints on this optimization (see Sections 4.2.2 to 4.2.4). Interfacing with a CORe Simulation and Optimization Model (CORSOM) for each reactor (see Section 2.5.4), the SOM passes a set of reactor-cycle energies and receives the minimum total reactor fuel revenue requirement to the horizon and the partial derivatives of this cost with respect to each of the cycle energies. These nuclear incremental cost data are then used to iterate toward the optimum set of cycle energies (see Section 4.4).

When the system nuclear fuel revenue requirement has been thus minimized, the supervisory task commences. This second task (see Section 4.5) merely involves present-valuing the non-nuclear period expenses and adding in the total
nuclear revenue requirement to determine the total operating revenue requirement for the particular possible alternative strategy under investigation. With the completion of this task, processing of the refueling and maintenance strategy is complete and optimization of the next such strategy may begin.

4.2 Elements of Optimization Problem in SOM

The following sections outline the elements of the SOM's optimization problem. In Section 4.2.1, the objective function of the optimization is first presented straightforwardly as the total system nuclear fuel revenue requirement. Then assumptions and simplifications are made to reduce the objective function to a form readily solvable by an iterative gradient technique. Next, the constraints on the optimization are discussed in detail.

Reviewing the context of this optimization, the principal SIM result passed to the System Optimization Model is the nuclear potential, $N_p$, which is equal to the sum of the subset of reactor period energy productions, $E_{rcp}$, for each period. As indicated in Section 3.3.3, each $N_p$ value is independent of the detailed loading order of the nuclear increments. Hence, for each period $p$ subset of $E_{rcp}$, there exist many possible combinations of each reactor's $E_{rcp}$ which will satisfy $N_p$. The SOM is able to determine these additional possible subsets of $E_{rcp}$ more rapidly than if the SIM is used repeatedly, thus eliminating the need for
more than one SIM calculation per period. The object of the SOM is then to determine, subject to certain feasibility constraints, which combination of these subsets of $E_{rcp}$ for each period in the entire planning horizon results in the minimum system revenue requirement.

The first constraint (see Section 4.2.2) ensures that each system production subset of $E_{rcp}$ satisfies the nuclear potential, $N_p$, that was calculated by the SIM for that period. Next, the reactor production constraints (see Section 4.2.3.1) put limits on each reactor's maximum and minimum period energy production. These represent the SIM cases when each nuclear unit's total upper capacity was loaded first or last, respectively, within the system upper nuclear capacity. Finally, a shape constraint (see Section 4.2.4) is used to select subsets of reactor-period productions, $E_{rcp}$, which are compatible with the shape of the equivalent load curve.

### 4.2.1 Objective Function

The optimization seeks to minimize $\overline{TC}$ ($\equiv \overline{RR}_N$), the system nuclear fuel revenue requirement, over the multi-year horizon as a function of $E$, the set of all $E_{rcp}$,

$$\text{minimize} \quad \overline{TC} = \overline{TC}(E) \quad (4.1)$$

Since $\overline{TC}$ is the sum of the various reactor fuel costs $\overline{TC}_r$ calculated by the CORSOM's, which, in turn, are really functions of the $E_{rc}$ cycle energies,
\[
\overline{TC} (\varepsilon) = \sum_{r=1}^{R} \overline{TC}_r (E_{r1}, E_{r2}, \ldots) \tag{4.2}
\]

As Section 2.3 pointed out, \(\overline{TC}_r\) is non-linear and non-separable. However, since \(\overline{TC}_r\) has been minimized by the CORSOM for the given set of \(E_{rc}\), it must be well-behaved in the sense that it is continuous and unimodal, increasing with increasing \(E_{rc}\). Hence \(\overline{TC}_r\) is differentiable and

\[
\lambda_{rc} = \frac{\partial \overline{TC}_r}{\partial E_{rc}} > 0 \tag{4.3}
\]

Equation (4.3) permits taking the total differential of Equation (4.2),

\[
d\overline{TC} = \sum_{r=1}^{R} \sum_{c=1}^{C} \frac{\partial \overline{TC}_r}{\partial E_{rc}} dE_{rc} \tag{4.4}
\]

Since \(\overline{TC}\) is a point function, given a cost \(\overline{TC}_t\) at \(\varepsilon^t\) trial set of \(E_{rcp}\), the cost \(\overline{TC}^{t+1}\) at any other set \(\varepsilon^{t+1}\) can be obtained by integrating Equation (4.4),

\[
\overline{TC}^{t+1} - \overline{TC}^t = \int_{\varepsilon^t}^{\varepsilon^{t+1}} \sum_{r=1}^{R} \sum_{c=1}^{C} \left( \frac{\partial \overline{TC}_r}{\partial E_{rc}} \right)_{\varepsilon^t} dE_{rc} \tag{4.5}
\]

(Section 5.6.1 of Chapter 5 refers to the integral on the right-hand side as the actual or true difference between \(\overline{TC}^t\) and \(\overline{TC}^{t+1}\), \(\sum_{act}^{t+1}\).)

To be rigorously accurate, the line integral must follow a tortuous route through the multi-dimensional space from
\[ E^t \text{ to } E^{t+1} \]. Thus, each partial derivative must be calculated along a different line segment connecting two adjacent intermediate points along the route. It is far easier to calculate each partial derivative only about the current trial point \( E^t \) itself, \( \left( \frac{\partial TC}{\partial E_{rc}} \right) E^t \).

If these derivatives are used to replace those in Equation (4.5), an error term \( \delta^{t+1} \) must be included to correct for the approximation,

\[
TC^{t+1} = TC^t + \delta^{t+1} + \int_{E^t}^{E^{t+1}} \sum_{r}^{R} \sum_{c}^{C} \left( \frac{\partial TC_r}{\partial E_{rc}} \right) dE_{rc} \tag{4.6}
\]

Since each differential is only about its own \( E_{rc}^t \), the integral limits reduce to \( E_{rc}^t \) to \( E_{rc}^{t+1} \) and the two summations may be taken outside,

\[
TC^{t+1} = TC^t + \delta^{t+1} + \sum_{r}^{R} \sum_{c}^{C} \int_{E_{rc}^t}^{E_{rc}^{t+1}} \left( \frac{\partial TC_r}{\partial E_{rc}} \right) dE_{rc} \tag{4.7}
\]

or

\[
TC^{t+1} = TC^t + \delta^{t+1} + \sum_{r}^{R} \sum_{c}^{C} \int_{E_{rc}^t}^{E_{rc}^{t+1}} \lambda_{rc}^t dE_{rc} \tag{4.8}
\]

Defining the double summation term as \( \sum_{EST}^{t+1} \), the estimated change in \( TC^t \),

\[
TC^{t+1} = TC^t + \delta^{t+1} + \sum_{EST}^{t+1} \tag{4.9}
\]
Provided that the error in the approximation or estimation $\mathcal{S}^{t+1}$ is sufficiently small (see Section 5.6.1), Equation (4.9) provides an excellent basis for re-formulating the non-linear objective function and hence, the optimization, into an iterative procedure:

Given a trial point $\mathcal{E}^t$ with cost $\overline{\text{TC}}^t$ and incremental costs $\lambda^t_{rc}$, the next feasible trial point $\mathcal{E}^{t+1}$ is determined that minimizes $\overline{\text{TC}}^{t+1}$.

Since $\overline{\text{TC}}^t$ is constant within the iteration, the minimization of $\overline{\text{TC}}^{t+1}$ may be replaced by the approximately equivalent minimization of $\Sigma^{t+1}_{\text{EST}}$. Using the new $\mathcal{E}^{t+1}$, the CORSOM's can then generate the corresponding $\overline{\text{TC}}^{t+1}_r$ and $\lambda^{t+1}_{rc}$. The next SOM iteration then seeks to minimize $\Sigma^{t+2}_{\text{EST}}$, and so on.

In general, convergence of $\mathcal{E}$ and $\overline{\text{TC}}$ may occur but globality of the optimum $\mathcal{E}^*$ and $\overline{\text{TC}}^*$ cannot be guaranteed. However, for the special case of a convex $\overline{\text{TC}} (\mathcal{E})$, both convergence and globality are guaranteed (54). That is,

\[ \frac{\partial^2 \overline{\text{TC}}_r}{\partial E^{2}_{rc}} \text{ must be } \geq 0 \quad (4.10) \]

or

\[ \frac{\partial}{\partial E_{rc}} \left( \frac{\partial \overline{\text{TC}}_r}{\partial E_{rc}} \right) = \frac{\partial \lambda_{rc}}{\partial E_{rc}} \text{ must be } \geq 0 \quad (4.11) \]
The work of Widmer (57) and Watt (55) have shown that this is a reasonable assumption—the nuclear incremental cost $\lambda_{rc}$ increases or, at least, does not decrease with the cycle energy $E_{rc}$. That is, each additional increment of cycle energy (i.e., reload enrichment) costs at least as much as the previous increment.

To summarize, given that $\overline{TC}(E)$ is convex, the iterative optimization will converge to the global optimum using as the objective function,

$$\minimize \sum_{EST} (E) = \sum_{R} \sum_{C} \int_{E_{rc}^t}^{E_{rc}^{t+1}} \lambda_{rc}^t dE_{rc} \quad (4.12)$$

The above objective function is actually not a function of the period productions, but only of the cycle subtotals, the $E_{rc}$ cycle energies. However, all of the various constraints on the optimization, discussed in the following Sections 4.2.2-4.2.4, are period constraints and involve $E_{rcp}$ explicitly.

**4.2.2 System Production Constraint**

The constraint on system production requires that in each period the reactors produce sufficient energy to meet the nuclear potential,

$$\sum_{p} E_{rcp} = N_p \quad \text{for all } p \quad (4.13)$$

Calculation of $N_p$ has already been discussed in Section 3.3.3.
4.2.3 Reactor Production Constraint

There are two types of reactor production constraints. The first, discussed in Section 4.2.3.1 brackets the permissible values of each reactor's production for each of the Z periods within the planning horizon,

\[ E_{rcp}^{\min} \leq E_{rcp} \leq E_{rcp}^{\max} \quad \text{for all } r \text{ and } p \]  

(4.14)

The second, discussed in Section 4.2.3.2, specifies the reactor energy production beyond the planning horizon. These horizon end conditions permit the CORSOM's to evaluate and cost (at least approximately) the reactivity requirements of cycles beyond the end of the planning horizon. The goal is to normalize strategy vs. strategy horizon end effects. To accomplish this,

\[ E_{rC} = E_{rcp} + E_{r,C,Z+1} \quad \text{for all } r \]  

(4.15)

where \( E_{r,C,Z+1} \) = energy held over for production by reactor \( r \) beyond the horizon cycle \( C \) (in fictitious period \( Z+1 \)). In addition, \( E_{r,C+1}, E_{r,C+2}, \) etc. are specified.

4.2.3.1 Typical Period

The reactor period production constraint [Equation (4.14)] merely establishes the limits on each reactor's production. For the trivial case when unit \( r \) is down for refueling in period \( p \),
\[ E_{\text{rcp}}^{\text{min}} = E_{\text{rcp}}^{\text{max}} = 0 \]  

The SOM pre-calculates the other minimums and maximums using results from SIM. Two important load-duration curves, \( F_{\text{min}} \) and \( F_{\text{max}} \), not previously discussed, are among these results (see Figure 4.1).

The \( F_{\text{min}} \) was the SIM's current \( F \) immediately prior to the deconvolution required to load the first nuclear upper increment of group 3 (see Figure 3.8). That is, \( F_{\text{min}} \) includes forced-outage allowances for all of the nuclear minimums (group 1) plus any must-run fossil minimums (group 2). This curve is used to determine the \( E_{\text{rcp}}^{\text{max}} \) since the maximum energy a reactor's upper increments can produce occurs when all of its remaining capacity, 

\[ k_r \equiv K_{rl} - K_{rl} = K_r - K_{rl} \]  

is loaded at the very beginning of this group 3.

Thus to determine \( E_{\text{rcp}}^{\text{max}} \), the following two step procedure is performed (see Figure 4.2) for each on-line reactor:

**Step 1:** From \( F_{\text{min}} \), which includes all on-line nuclear minimums, deconvolve the initial increment of unit \( r \),
Figure 4.1

$F_{\min}$ and $F_{\max}$ Load-Duration Curves Required by SOM

- $F_{\min}$ includes all on-line nuclear units at minimum capacity
- $F_{\max}$ includes all on-line nuclear units at maximum capacity

$P_e$: Equivalent Load (MW)

$P_{\min}$, $P_{\max}$

$F$, Probability ($P_e \geq$)
Figure 4.2

Calculation of $E_{\text{rcp}}^{\text{max}}$

NUCLEAR UPPER INCREMENTS (GROUP 3)

$p_{\text{MIN}} = F_{\text{r1}}^{\text{w}}$

DECONVOLVE $k_{\text{r1}}$ TO YIELD $F_{\text{r1}}^{\text{wo}}$

$k_T$

$F_e$, PROBABILITY ($P_e \geq$)

$p_{\text{MIN}}$

$p_{\text{MAX}}$

$P_e$, EQUIVALENT LOAD (MW)

$E_{\text{rcp}}^{\text{max}}$

EMAX, $a_1 = U - 0.5$

$kr_1$

MAXIMUM DEMAND ON UNIT $r$'S UPPER INCREMENTS
Step 2: Since $F_{\text{rl}}^\infty$ is the proper curve for loading the remaining $k_r \text{ MW}$ in order to maximize $E_{\text{rcp}}$,

$$
E_{\text{rcp}}^{\max} = E_{\text{rcp}}^0 + T' \int_{P_{\text{min}}}^{P_{\text{min}} + k_r} F_{\text{rl}}^{\infty} \text{d}P_e
$$

(4.19)

where $E_{\text{rcp}}^0$ is the invariant energy production of the unit's first $K_{r1} \text{ MW}$.

To determine $E_{\text{rcp}}^{\min}$ requires the $F_{\text{rl}}^{\max}$ of Figure 4.1, which represents the SIM's current $F$ after the last nuclear upper increment of group 3 has been convolved in. That is, $F_{\text{rl}}^{\max}$ includes any fossil must-run minimums plus all of the nuclear maximums. Whereas $E_{\text{rcp}}$ was maximized when $k_r \text{ MW}$ were first in group 3, minimum reactor energy production for the period occurs when unit $r$'s $k_r \text{ MW}$ are the very last in group 3 to be loaded. Thus, the following two step procedure is applied to $F_{\text{rl}}^{\max}$ for each reactor (see Figure 4.3):

Step 1: From $F_{\text{rl}}^{\max}$, which includes all on-line nuclear units at their maximum capacity, deconvolve the entire $K_{r1} \text{ MW}$ of unit $r$,

$$
F_{\text{rl}}^{\infty} = \frac{1}{P} \left[ F_{\text{max}}(P) - q_r F_{\text{rl}}^{\infty}(P - K_{r1}) \right]
$$

(4.20)
Figure 4.3
Calculation of $E_{rcp}^{\text{min}}$

NUCLEAR UPPER INCREMENTS (GROUP 3)

$F_{\text{MAX}} = F_{r\text{I}}$

DECONVOLVE $K_{r\text{I}}$ TO YIELD $F_{r\text{I}}^{\text{WO}}$

MINIMUM DEMAND ON UNIT $r$'s UPPER INCREMENTS

$k_r$

$p_{\text{MIN}}$, $p_{\text{MAX}}$, $F_e$, EQUIVALENT LOAD (MW)
Step 2: Since $F_{rI}^{WO}$ is the proper curve for loading the remaining $k_r$ MW in order to minimize $E_{rcp}$,

$$E_{min} = E_{rcp} + T' \int_{P_{max}}^{P_{max} - k_r} F_{rI}^{wo} \, dP_e$$  \hspace{1cm} (4.21)

4.2.3.2 Horizon End Condition

To properly evaluate fuel cycle costs (i.e., reload requirements and discharge characteristics) incurred within the planning horizon, each reactor's CORSOM must receive not only the energy of each of the $C$ "included" cycles within the horizon, but also estimated cycle energies for several "excluded" cycles beyond the horizon. The specified end condition should match as closely as possible the same general operating philosophy (i.e., capacity factor) anticipated for the strategy's included cycles. That is, excluded cycles continue with similar cycle lengths in both energy and time as those within the horizon, not return to some arbitrary state, regardless of the particular included strategy.

To effect this requires an estimate of $E_{r,C,Z+1}$, the amount of cycle $C$ energy held over beyond the horizon (for fictitious period $Z+1$) for production before the next refueling (see Figure 4.4),

$$E_{rC} = \sum_{t} E_{rC_t} + E_{r,C,Z+1}$$  \hspace{1cm} (4.22)
Figure 4.4

Horizon End Condition

TIME (PERIOD)

END OF PLANNING HORIZON
(i.e., EXPLICITLY INCLUDED PERIODS)
In addition, several completely excluded cycle energies are estimated \( (E_{r,C+1}, E_{r,C+2}, \text{ etc.}) \). Total system nuclear production from all reactors during the excluded cycles should be held constant for all refueling and maintenance strategies to ensure similar system-wide core energy content at the end of the planning horizon. Recall that the goal is to normalize strategy vs. strategy horizon end effects.

Since the end condition exists only in deference to the CORSOM's calculational requirements, it is not included explicitly in the mathematical formulation of the SOM's optimization problem summarized in Section 4.3.

4.2.4 Shape Constraint

The shape constraint is used to guarantee that the reactor energy productions within the period are, in the aggregate, compatible with the given equivalent load shape. In the Booth-Baleriaux calculations of the SIM, the various increments of each unit are assigned various segments of the equivalent load curve on a MW for MW basis. Summing the \( I \) increments of energy production \( E_{ri} \) for each unit,

\[ E_r = \sum E_{ri} \quad (4.23) \]

These \( E_r \) represent each unit's energy production for the period using the specified increment-by-increment loading order. By the nature of the SIM calculation, any detailed
loading order specifies a set of feasible \( E_r' \)'s for the period (i.e., a set of \( E_r' \)'s which are compatible with the shape of the equivalent load curve).

However, the optimization variable in SOM is not the detailed loading order, but each nuclear unit's period production \( E_{rcp} \). Thus, the shape compatibility question becomes: "For a given subset of reactor-period energy productions (\( E_{rcp} \) for all \( r \) at \( p \)) whose sum equals the required period nuclear potential \( N_p \) from SIM, could a corresponding detailed reactor loading order be found that satisfies the period's equivalent load shape (calculated by SIM) yet results in the SOM's postulated \( E_{rcp} \)?" The shape constraint attempts to quantify the feasibility of finding such a loading order (yet circumvents actually having to perform the search or SIMulation).

The general form of the shape constraint will be shown to be second-order,

\[
\sum_{r_p} c_{1rp} E_{rcp} + \sum_{r_p} c_{2rp} E_{rcp}^2 \leq c_p
\]  

(4.24)

where \( c_{1rp}, c_{2rp} \) and \( c_p \) are constants pre-calculated by the SOM from SIM results. While the system and reactor production constraints [Equations (4.13) and (4.14), respectively] are linear, (i.e., first order), the shape constraint Equation (4.24) is non-linear. As with all but the most trivial problems in operations research, non-linearities greatly complicate the optimization algorithm (see Section
4.4.3). The current discussion, however, concentrates solely on understanding "why" and "how" the shape constraint is formulated in the first place.

4.2.4.1 Purpose

To understand why the shape constraint is necessary, consider the following example which would otherwise be permitted by the SOM as a feasible solution. Assume the customer loads remain as on the Reference Utility System in Figure 2.9. However, assume for the sake of this example that the utility system itself consists of only six identical 400 MW nuclear reactors which, for simplicity in the example, have no forced-outages ($p_f = 100\%$) and no minimum load constraint; therefore, $P_D = P_e$. Figure 4.5 portrays system production calculated by the SIM for the specified startup and loading order. Note that for this feasible production schedule, the SIM results indicate nuclear system production of

$$N_p = D_T = 949 \text{ GWH} \quad (4.25)$$

and reactor production limits equivalent to

$$E_{rcp}^{\text{max}} = 292 \text{ GWH} \quad (4.26)$$

$$E_{rcp}^{\text{min}} = 0 \text{ GWH} \quad (4.27)$$
Figure 4.5

Six Identical Reactors versus Reference Utility Customer Demand

\[ D_T = 949 \text{ GWH} = N_D \]

\[ \bar{X} = F_D \text{ (EQUIVALENT TO ALL SIX REACTORS AT 158.17 GWH)} \]

\( P_e, \text{ EQUIVALENT LOAD (MW)} \)

\( F, \text{ PROBABILITY (} P_e \geq \text{)} \)

730 HOUR MONTH

UNIT 1
UNIT 2
UNIT 3
UNIT 4
UNIT 5
UNIT 6

292 GWH
292
262.8
94.9
17.3
0.0

GWH PROD.
Inserting these values in the two production constraints [Equation (4.13) and (4.14)] and ignoring any shape constraint, the SOM would be perfectly justified in postulating the production schedule shown in Figure 4.6 since the desired total energy \( N_p \) (proportional to area under the curve) is supplied. Comparing this production shape with that of the customers \( (F_D) \), the shape infeasibility is readily apparent since production never reaches a power level greater than 1400 MW while the customer demand is greater than that 20% of the time.

Thus, the optimization model must include either (a) some method of forcing each subset of \( E_{rcp} \) derived in the SOM to satisfy the load shape, or (b) include a constraint, or posteriori check, which rejects from further consideration any subsets of \( E_{rcp} \) which cannot satisfy the load shape. The latter method, referred to as a "shape constraint," is utilized in the model presented here.

Having established the necessity of a shape constraint, how might the "shape" be quantified?

First of all, the shape most indicative of the demands to be satisfied by each nuclear unit is not the direct customer load-duration curve \( F_D \) (unless all \( p_r \) are actually equal to 100%), but the equivalent load-duration curve \( F_e \), which includes not only direct, but also indirect, customer loads. (Section 4.2.4.3 discusses the practical means by which the SOM determines \( F_e \) given \( F_{\text{min}} \) and \( F_{\text{max}} \).) Furthermore, by focusing attention only on the nuclear units and assuming their size and economics make them all must-run
Figure 4.6

Infeasible Six Reactor Production Schedule

POSTULATED REACTOR PRODUCTION SHAPE

F. PROBABILITY ($P_e^-$)

$P_e$, EQUIVALENT LOAD (MW)

UNIT 6  UNIT 5  UNIT 4  UNIT 3  UNIT 2  UNIT 1

292 GWH  292 GWH  292 GWH  73

0.0  400  800  1200  1600  2000  2400

0.0  1.0  0.5
units, the pertinent range of $F_e$ can be reduced to that segment served by the nuclear upper increments of the $R'$ available (on-line) nuclear units (group 3 of Figure 4.1). Henceforth, the term "system shape" and symbol $F_e$ refer to that segment of the equivalent load curve over the range of loads running from zero MW upper nuclear capacity to the system total availability-based nuclear upper increment capacity $k_T'$ (i.e., each unit's first increment is excluded from the discussion since all $K_{r1}$ MW are base-loaded),

$$k_T' = \sum R' \k_r = \sum (K_rI - K_{r1})$$

(4.28)

In order to characterize the production schedule in terms of the optimization variables $E_{rcp}$, consider the capacity factors of the units. (For convenience, the $E_{rcp}$ notation is shortened to $E_r$ since the same period $p$ applies to all reactors and cycle $c$ is immaterial to the current discussion.) As Widmer (57, 58) stated with elegant simplicity,

$$E = KLT$$

(4.29)

where

$E =$ electric energy production

$K =$ rated electric capacity

$L =$ average capacity factor

$T =$ total length of time (i.e., including all outages)
Equation (4.29) actually serves to define $L$,

$$L = \frac{E}{kT}$$  \hspace{1cm} (4.30)

With the current discussion limited to any time period of length $T'$ during which the unit (with a performance probability $p$) is never down for scheduled maintenance or refueling, a more meaningful parameter is the availability-based capacity factor $L'$

$$L' = KL'T'p$$  \hspace{1cm} (4.31)

or

$$L' = \frac{E}{kT'T'}$$  \hspace{1cm} (4.32)

In words, $L'$ represents the capacity factor the unit experienced during the period's $pT'$ available hours that it was not down due to maintenance or refueling ($T-T'$) or forced-outages $[(1-p)T']$. By comparing Equation (4.31) with Equation (2.24) integrated over the appropriate segment of the complete $F_e$, 

$$K_rL'T'p_r = T'p_r \int_0^{K_r} F_e(P_e) dP_e$$  \hspace{1cm} (4.33)

or,

$$L' = \frac{1}{K_r} \int_0^{K_r} F_e(P_e) dP_e$$  \hspace{1cm} (4.34)
Hence, \( L_r' \) represents the average value of \( F_e \) in those segments placing demand on unit \( r \).

Since the discussion is limited to the nuclear unit's upper (i.e., \( I-1 \)) increments, define \( l_r' \) as the availability-based increment capacity factor for unit \( r \). Thus,

\[
E_r = \sum E_{ri} = E_{rl} + k_r l_r' T' p_r \tag{4.35}
\]

or

\[
l_r' = \frac{E_r - E_{rl}}{k_r T' p_r} = \alpha_r E_r - \beta_r \tag{4.36}
\]

where

\[
\alpha_r = \frac{1}{k_r T' p_r} \tag{4.37}
\]

\[
\beta_r = \frac{E_{rl}}{k_r T' p_r} \tag{4.38}
\]

Given each reactor's postulated production, \( E_{rcp}' \) (the \( p \) subset for all \( r \) resulting in \( N_p \) in toto), each \( l_r' \) can be calculated and then ordered and plotted in decreasing magnitude. The resulting curve, whose abscissa is defined as \( P_r' \), is labeled the "average reactor shape" \( F_r' \) in Figure 4.7c.

Using Figure 4.7a as an illustration, the segments of \( F_e \) used for loading each reactor's upper capacity \( k_r \) can be replotted separately as in Figure 4.7b. The average \( F_e \) for each reactor's upper increments is then \( l_r' \). Reordering the
Figure 4.7 Decomposition and Reordering of System Shape

Note: First increment of each unit (unit shape) is base-loaded. Difference between upper and lower increments maximizes differences between units.
reactor segments of Figure 4.7b with the largest $\lambda'_r$ first, the detailed reactor shape $F_r$ of Figure 4.7c results, defining the abscissa $P_r$, the composite reactor upper increment power. The system shape $F_e(P_e)$ of Figure 4.7a has merely been segmented and then reordered into the detailed reactor shape of $F_r(P_r)$ of Figure 4.7c on the basis of the average demand on each unit's upper increments $\lambda'_r$. Mathematically speaking, $F_r(P_r)$ is a one-to-one mapping of $F_e(P_e)$ since for every element of (point along) $F_e$ at $P_e$, there exists a corresponding element of (point along) $F_r$ at $P_r$. (However, in general, $P_e \neq P_r$.) Thus, the total area under the three shapes (i.e., for all $k'_T$ MW of on-line nuclear upper increment capacity) is the same,

$$\int_0^{k'_T} F_e(P_e) dP_e = \int_0^{k'_T} F_r(P_r) dP_r = \int_0^{k'_T} F_r(P_r) dP_r$$ (4.39)

The example in Figure 4.7 is, by definition, feasible since the detailed upper increment loading order resulting in each $E_r$ (recall that each $K_{rl}$ MW are base-loaded) and $N_p$ in toto is clearly specified in Figure 4.7a. However, recall that in the SOM, only the $F_e$ system shape to be satisfied and a postulated subset of $E_r$'s are specified (not the detailed loading order). Hence, too little information is known to determine the detailed $F_r(P_r)$ as in Figure 4.7c. Nonetheless, the $F_r$ average reactor shape can be determined for the postulated subset of $E_r$'s. By
applying Equation (4.36), each reactor's $l'_r$ can be calculated and placed in descending order, resulting in the desired $F_r$.

The question of feasibility can then be stated as follows:

Given a postulated subset of $E_r$'s (and the resulting "postulated" average reactor shape $F_r$ on the upper increments), does there exist at least one intra-nuclear upper increment loading order such that the on-line reactors can indeed satisfy the given detailed system shape $F_e$?

A detailed loading order need not be determined, merely its existence established. If one exists, the postulated set of $E_r$'s represent a feasible means of operating the nuclear units; if none exists, then the postulated schedule is infeasible.

Two methods were considered for determining the existence of such a loading order: (1) area method and (2) variance method. The area method (see Appendix B), though rigorous (i.e., necessary and sufficient), involved an inordinate amount of computer data handling and storage and, therefore, was not implemented.

Utilizing the other (approximate) variance method, the shape constraint (derived in Section 4.2.4.2 and implemented per Section 4.2.4.3) is used to eliminate postulated subsets of $E_r$'s which result in infeasible shapes by comparing a single parameter, the "variance" of the shape produced by the postulated $E_r$'s against a similar parameter for the
SIM-calculated system shape $F_e$.

4.2.4.2 Mathematical Basis

To derive the shape constraint, consider the $F_e(P_e)$ system shape on the upper nuclear increments shown in Figure 4.7a. As a measure of the system shape, compare the shape with its mean $ar{\ell}$,

$$\bar{\ell} = \frac{1}{k_T} \int_0^{k_T'} F_e(P_e) dP_e$$  \hspace{1cm} (4.40)

Defining $S^2$ as the "variance" of the system shape compared with its mean,

$$S^2 = \frac{1}{k_T} \int_0^{k_T'} (F_e - \bar{\ell})^2 dP_e$$  \hspace{1cm} (4.41)

For a known feasible solution, the $S^2$ variance will be the same whether integrated directly from 0 to $k_T'$ (see Figure 4.7a), or first segmented into the respective detailed MW-by-MW reactor load shapes, reordered and then integrated (see Figure 4.7c).

$$S^2 = \frac{1}{k_T} \int_0^{k_T'} (F_r - \bar{\ell})^2 dP_r$$  \hspace{1cm} (4.42)

Breaking this integral into a sum over each of the $R'$ on-line reactors,
\[ S^2 = \frac{1}{\mathcal{R}_T} \sum \int_{P_r^o}^{P_r^o + k_r} (F_r - l_r')^2 \, dP_r \]  

(4.43)

Adding and subtracting \( l_r' \) inside the integrals of the summation,

\[ S^2 = \frac{1}{\mathcal{R}_T} \sum \int_{P_r^o}^{P_r^o + k_r} (F_r - l_r' + l_r' - l_r')^2 \, dF_r \]  

(4.44)

or

\[ S^2 = \frac{1}{\mathcal{R}_T} \sum \int_{P_r^o}^{P_r^o + k_r} \left[ (F_r - l_r')^2 + (l_r' - \bar{\ell}')^2 + 2(F_r - l_r')(l_r' - \bar{\ell}') \right] \, dP_r \]  

(4.45)

The third term inside the brackets vanishes since \( (l_r' - \bar{\ell}') \) equals a constant and

\[ l_r' \equiv \frac{1}{k_r} \int_{P_r^o}^{P_r^o + k_r} F_r \, (P_r) \, dP_r \]  

(4.46)

for then

\[ \int_{P_r^o}^{P_r^o + k_r} 2(F_r - l_r')(l_r' - \bar{\ell}') \, dP_r = 2(l_r' - \bar{\ell}') \int_{P_r^o}^{P_r^o + k_r} (F_r - l_r') \, dP_r \]  

(4.47)

\[ = 0 \]

Thus,
\[
S^2 = \frac{1}{k_r'} \sum_{p_r'}^{R'} \left( F_r - \bar{e}_r' \right)^2 dp_r + \frac{1}{k_r'} \sum_{p_r'}^{R'} k_r' \left( l_r' - \bar{e}_r' \right)^2 \tag{4.48}
\]

\[
S^2 = V^2 + W^2 \tag{4.49}
\]

where \( V^2 \) = total internal variance of sub-segments of \( F_r \) for each reactor (i.e., requires detailed loading order)

\( W^2 \) = weighted sum of squares of reactor average versus system average of \( F_e \) (i.e., not dependent on MW-by-MW loading order, only average \( F_r \) over each \( k_r \) MW)

For a feasible \( E_r \) subset, \( V^2 \) must be non-negative since the integrand is squared. Therefore, if \( V^2 \) is negative for some other postulated production schedule when calculated by taking the difference in the calculated values of \( S^2 \) [Equation (4.41)] and \( W^2 \) [Equation (4.48)], that postulated schedule is clearly infeasible. Note that the converse is not true. If \( (S^2 - W^2) \) is greater than or equal to zero, feasibility is not guaranteed. The following Section 4.2.4.3 discusses the practical implementation of this approximate constraint.
Typical values of $s^2$ calculated in this study are on the order of 0.01 to 0.03, while the theoretical maximum value is 0.25 for the pathological case of

$$F_e(P_e) = \begin{cases} 1 & 0 \leq P_e < 0.5k'_T \\ 0 & 0.5k'_T < P_e \leq k'_T \end{cases}$$

(4.50)

For the infeasible example of Figure 4.6, $s^2 = 0.201$ while the reactor summation term $W^2$ has a value of 0.217. Thus, $v^2 = s^2 - W^2 = -0.016$, a highly infeasible value.

4.2.4.3 Practical Implementation

Practical implementation of Equation (4.49) as the SOM's shape constraint involves (1) determining the system shape $F_e$ given the SIM's $F^{\text{min}}$ and $F^{\text{max}}$ (see Figure 4.1) and (2) incorporating a $V^2_{\text{REJ}}$ rejection level on $v^2$ to allow flexibility in the model's handling of the constraint that $v^2 = s^2 - W^2 \geq 0$.

The practical definition of $F_e$ is the demand curve used for loading each MW according to Equation (2.24). For the first MW of the nuclear upper increments, the deconvolve-load-convolve sequence of the multiple increment algorithm of Section 3.3.2.2 must be applied to $F^{\text{min}}$. Since the identity of the first nuclear upper increment to be loaded is arbitrary at this point, a hypothetical unit with the average values of $p_r$ and $k_r^1$ which gives the same average MW of outage would appear to be useful,
\[
\overline{p_{r_{\text{min}}}} = \sum_{r'} p_r K_{rI} / \sum_{r'} K_{rI} \quad (4.51)
\]
\[
\overline{K_{rI}} = \frac{1}{R'} \sum_{r'} K_{rI} \quad (4.52)
\]

Deconvolving this unit per Equation (3.55),

\[
F_{rI}^{w0} (P_e) = \frac{1}{p_{\text{min}}} \left[ F_{rI}^{\text{min}} (P_e) - (1 - \overline{p_{r_{\text{min}}}}) F_{rI}^{w0} (P_e - \overline{K_{rI}}) \right] \quad (4.53)
\]

This \( F_{rI}^{w0} \) is the average curve used to load the first MW of the nuclear upper increments. In a similar manner, an \( F_{rI}^{w0} \) can be determined from \( F_{rI}^{\text{max}} \) that estimates the curve used for loading the last MW of the nuclear upper increments:

\[
\overline{p_{r_{\text{max}}}} = \sum_{r'} p_r K_{rI} / \sum_{r'} K_{rI} \quad (4.54)
\]
\[
\overline{K_{rI}} = \frac{1}{R'} \sum_{r'} K_{rI} \quad (4.55)
\]

and

\[
F_{rI}^{w0} (P_e) = \frac{1}{\overline{p_{r_{\text{max}}}}} \left[ F_{rI}^{\text{max}} (P_e) - (1 - \overline{p_{r_{\text{max}}}}) F_{rI}^{w0} (P_e - \overline{K_{rI}}) \right] \quad (4.56)
\]
Figure 4.8 presents $F_{\text{WO}}^r$ and $F_{\text{WO}}^l$ for the $F_{\text{min}}$ and $F_{\text{max}}$ of Figure 4.1. Since each $F_{\text{WO}}^r$ is equal to $F_e$ at a particular point of application,

Point A: \[ F_{\text{WO}}^r(0) = F_e(0) \] (4.57)

Point B: \[ F_{\text{WO}}^l(k'_T) = F_e(k'_T) \] (4.58)

then $F_e(P_e)$ must trace a path connecting points A and B of Figure 4.8. Thus, $F_e$ can be simply approximated by interpolation over the range $0 \leq P_e \leq k'_T$,

\[ F_e(P_e) = \left(1 - \frac{P_e}{k'_T}\right) F_{\text{WO}}^r(P_e) + \frac{P_e}{k'_T} F_{\text{WO}}^l(P_e) \] (4.59)

With $F_e$ approximated, $\overline{\ell}'$ and $S^2$ are easily calculated (see Figure 4.9),

\[ \overline{\ell}' = \frac{1}{k'_T} \int_0^{k'_T} F_e(P_e) \, dP_e \] (4.40)

\[ S^2 = \frac{1}{k'_T} \int_0^{k'_T} (F_e - \overline{\ell}')^2 \, dP_e \] (4.41)

With $\overline{\ell}'$ and $S^2$ pre-calculated by the SOM before the iterative optimization procedure begins (see Section 4.4), Equation (4.49) is implemented as the shape constraint on
Figure 4.8
Approximation of $F_e$

NUCLEAR UPPER INCREMENTS (GROUP 3)

$F_e$, $F_{e_1}$, $F_{e_2}$

$P_e$, SYSTEM EQUIVALENT LOAD (MW)
Figure 4.9

Comparison of System Shape and Postulated Average Reactor Shape

\[ F_e \text{ SYSTEM SHAPE} \]

\[ \ell'_{r} - \bar{l'} \]

\[ \bar{l'} \text{ POSTULATED AVERAGE REACTOR SHAPE (} \ell'_{r} \text{)} \]

[DETERMINED VIA EQ. (4.36)]

\[ (F_e(P_e) - \bar{r'}) \]

\[ P_e, \text{ EQUIVALENT LOAD (MW)} \]

ON NUCLEAR UPPER INCREMENTS
each iteration's postulated set of $E_r$. This involves
(1) using Equation (4.36) to calculate $l'_r$ for each postulated
$E_r$,

$$l'_r = \alpha_r E_r - \beta_r$$ (4.36)

(2) calculating $W^2$ from the resulting $l'_r$ (see Figure 4.9),

$$W^2 = \frac{1}{k'} \sum_{r} k_r (l'_r - \bar{l})^2$$ (4.48)

and (3) testing the resultant $V^2$ ($= S^2 - W^2$) versus a $V^2_{REJ}$
rejection level designed to establish feasibility, not
merely infeasibility, as discussed below.

Rearranging Equation (4.49),

$$V^2 = S^2 - W^2$$ (4.60)

This is the convenient form of Equation (4.49) since deter-
mining $V^2$ by difference does not required a detailed loading
order (which may not even exist). For $V^2 < 0$, the postulated
production schedule is infeasible; $V^2 \sim 0$, may be infeasible;
$V^2 \gg 0$, almost certainly feasible. To implement the con-
straint, a $V^2_{REJ}$ rejection level is introduced such that if
$V^2 \leq V^2_{REJ}$, the postulated schedule is rejected as probably
infeasible. Figure 4.10 presents a visual interpretation of
the implementation.
Figure 4.10
Implementation of \( V_{Rej}^2 \), Period Shape Test

\[ S^2 - W^2 = V^2 \]

\[ V^2 \geq V_{Rej}^2 \]

Therefore accept postulated production schedule.
Note the flexibility of a model allowing $V_{REJ}^2$ as an input parameter:

(1) If $V_{REJ}^2 = 0$, Equation (4.48) holds directly with $V^2 > 0$ being required, or (2) If $V_{REJ}^2 \leq -0.25$, the shape constraint is effectively nullified. To be accepted $W^2$ must be

$\leq S^2 - V_{REJ}^2 = S^2 + 0.25$. Theoretically, $(W^2)_{max} = 0.25$ (see Section 4.2.4.2) and $(S^2)_{min} = 0$. Thus, $W^2$ is always

$\leq S^2 + 0.25$ and, hence, always accepted.

To summarize the complete formulation of the shape constraint for period $p$, the $E_r$ notation returns to $E_{rcp}$. Hence, a postulated period production schedule is not rejected as infeasible if

$$W_p^2 \leq S_p^2 - V_{REJ}^2$$

(4.61)

or

$$\sum_{r=1}^{R_p} \frac{\lambda_r (\alpha_{rp} E_{rcp} - \beta_{rp} - \mu_{p})^2}{\sum_{r=1}^{R_p} \lambda_r} \leq S_p^2 - V_{REJ}^2$$

(4.62)

Note the existence of second-order terms ($E_{rcp}^2$) as was indicated in Equation (4.24).
4.3 Mathematical Statement of Optimization Problem

Summarizing the elements of the optimization problem formulated in Section 4.2, the problem can be stated succinctly as,

\[
\text{minimize } \bar{T}C(\mathcal{E}) = \sum_{r} \bar{T}C_r (\{E_{rc}\})
\]

or equivalently

\[
\text{minimize } \sum_{E_{ST}}^{t+I} (\mathcal{E}) = \sum_{r} \sum_{c} \int_{E_{rc}^t}^{E_{rc}^{t+1}} \lambda_{rc}^{t} dE_{rc}
\]

such that the following period constraints are met for System Production:

\[
\sum_{r}^{R} E_{rcp} = N_p \quad \text{for all } p \tag{4.13}
\]

Reactor Production:

\[
E_{rcp}^{\min} \leq E_{rcp} \leq E_{rcp}^{\max} \quad \text{for all } r \text{ and } p \tag{4.14}
\]

and Shape:

\[
\sum_{r=1}^{R_p'} \lambda_r \left( \alpha_p E_{rcp} - \beta_p - \overline{e}_p \right)^2 \leq \frac{S_p^2 - V_{REJ}^2}{\sum_{r=1}^{R_p'} \lambda_r} \tag{4.62}
\]
4.4 Method of Optimization

In choosing a method of optimization, the size of the problem itself must be considered. Suppose a utility with eight reactors desires to optimize the system refueling strategy over the next six years using time periods two weeks long. Then, there will be $Z \approx 150$ time periods, each of which has two constraints [Equations (4.13) and (4.62), one of which is non-linear]. Each of the $R \cdot Z = 1200$ optimization variables in $E$ has a lower and an upper limit (2400 more constraints). The final total: 1200 variables to be optimized subject to 2700 constraints—a very large optimization problem, particularly if solved in an iterative fashion.

The schematic diagram of a two-stage iterative optimization procedure is shown in Figure 4.11. The optimization is initiated by the precalculation of constraint limits (Block A) based on the output supplied by the SIM. Then for each outer shape iteration, $s$, the inner cost iteration loop, consisting of the network program without any shape constraints (Block B) and the CORSOM's (Block C), operates within the remaining constraints. The inner loop's output is a complete set of optimized reactor-cycle energies, $E_{rc}^*$, which results in the minimum nuclear fuel revenue requirement for the system, $\overline{TC}^*_s$. In the second stage, the network program of Block D is used to apportion each reactor-cycle energy in this set among the various reactor-periods
Figure 4.11

SOM Optimization Scheme

SIM OUTPUT

START

\[ t = s = 0 \]

PRE-CALCULATE CONSTRAINTS

\[ \text{MIN. } \sum_{\text{EST}}^{t+1} \]

CONSTRANST:

\[ R \]

\[ \sum_{r} E_{rcp} = W_p \]

\[ (2) E_{\text{min},s}^{rcp} \leq E_{rcp} \leq E_{\text{max},s}^{rcp} \]

\[ \{E_{rc}^{t+1}\} \]

INNER COST ITERATION

\[ t = t + 1 \]

CORSOM's

MIN. \[ W_s^{\circ} \]

(SEE SECTION 4.4.3)

CONSTRANST:

\[ (1), (2) \text{ ABOVE AND} \]

\[ (3) E_{rc} = E_{rc}^{\circ} \]

\[ \{E_{rc}^{t+1}\} \]

OUTER SHAPE ITERATION

\[ \text{ALL } V_p^2 < V_{RE1} \]

YES

NO

\[ s = s + 1 \]

ALTER \[ E_{\text{min},s}^{rcp} \text{ AND } E_{\text{max},s}^{rcp} \]

FOR REJECTED PERIODS
making up a reactor-cycle. The objective is to minimize the likelihood that the shape constraint for any period will be violated, \( M_{*,s} \). Then, Block E compares the "variance", \( V_p^2 \), for each period of the resulting set of reactor-period energy productions, \( \{E_{rcp}^{*,s}\} \), with the preselected shape rejection criterion, \( V_{REJ}^2 \). If the shape of any period violates the criterion, another outer shape iteration is begun by decreasing the range of the permissible reactor-period energy productions for all reactors supplying energy in each rejected period. When all period shapes are accepted, the optimization of the SOM is complete. The resulting optimized (i.e., minimized) nuclear fuel revenue requirement, \( TC^{\bullet} \), is combined with the non-nuclear operating revenue requirements to produce the system's total optimized operating revenue requirement (as shown in Figure 2.22) for the particular alternative refueling and maintenance strategy under investigation.

While many iterative, non-linear optimization techniques seek the global optimum by operating within the feasible \( E \) hyperspace, this two-stage technique approaches the optimum from without, i.e., from the infeasible region. Consequently, instead of each iteration decreasing the objective function, the objective function increases as feasibility is approached, giving a lower bound for the more feasible solution at the next iteration (see Section 5.6.2).
### 4.4.1 Concept of Nuclear Energy Supply Network

Since the only non-linear constraint [Equation (4.62)] is not considered explicitly in either sub-optimization of Figure 4.11, the remaining constraints are linear. In fact, because the resulting sub-optimizations deal with a single commodity (nuclear energy production) in a strict one-to-one (reactor) supply and (customer) demand sense, the constraints form a nuclear energy supply network. Figure 4.12 presents such a network configuration for a 3 reactor, 24 period (month) example. (Numbers are displayed for the nuclear potentials to emphasize the fact that these are fixed constraints throughout all of the iterations for a particular refueling and maintenance strategy.) Nuclear energy is allocated (supplied) to each reactor-cycle. Within each cycle, the energy is allocated to the pertinent periods so as to satisfy the system nuclear potentials (demanded). The sum of any column must equal the energy supplied (or extracted) during that particular reactor-cycle while the sum of any row must equal its required nuclear potential [Equation (4.13)]. The range of each $E_{r, cp}$ is also constrained via Equation (4.14) (presented in Table 4.1 but not shown explicitly on Figure 4.12) leading to the term "capacitated" network.

Each of the sub-optimizations in the following sections thus seeks to determine that $E$ set of $E_{r, cp}$ that satisfies these network constraints, yet minimizes its respective objective function.
Figure 4.12

Sample Network Configuration

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<th>REACTOR 3 CYCLE:</th>
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### Table 4.1.

Reactor Production Limits for 3 Reactor,
24 Period Example

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<td>703</td>
<td>722</td>
<td>743</td>
<td>763</td>
<td></td>
</tr>
</tbody>
</table>

All \( E_{rcp} \) in GWH
4.4.2 Inner Iteration on Nuclear Cost

Each inner cost iteration of Figure 4.11 solves the following sub-optimization problem:

\[
\text{minimize } \sum_{E_{ST}}^{t+1} (E^{t+1}) = \sum_{R} \sum_{C} \int_{E_{rc}}^{t} \lambda_{rc} dE_{rc} \tag{4.12}
\]

such that

\[
\sum_{R}^{E_{rcp}} = N_{p} \quad \text{for all } p \tag{4.13}
\]

and

\[
E_{rcp}^{\text{min}} \leq E_{rcp} \leq E_{rcp}^{\text{max}} \tag{4.14}
\]

Inner iterations continue until \( E^{t+1} \) converges to \( E^{*} \). Critical to the minimization of Equation (4.12) is the representation of the incremental cost curve \( \lambda_{rc}^{t} \) as a function of \( E_{rc}^{t} \). Figure 4.13 presents a typical true incremental cost curve and two approximations to it:

(1) linear approximation,

\[
\lambda_{rc}^{t} = a_{rc}^{t} E_{rc}^{t} + b_{rc}^{t} \tag{4.63}
\]

and (2) a "stair-step" approximation having the same areas as the \( \Delta \) GWH segments of the true curve,

\[
\lambda_{rc}^{t} = \lambda_{rc}^{t+1} \quad E_{rc}^{t} - \Delta \leq E_{rc} < E_{rc}^{t} \tag{4.64}
\]

\[
= \lambda_{rc}^{t+1} \quad E_{rc} < E_{rc} \leq E_{rc}^{t} + \Delta
\]
Figure 4.13

Typical Incremental Cost Curve and Approximations

STAIR-STEP APPROXIMATION

LINEAR APPROX.: 
\[ \lambda^{t}_{rc} = a^{t}_{rc} E^{t}_{rc} + b^{t}_{rc} \]

"TRUE" CURVE

\[ \lambda^{tt}_{rc} \]

MINIMUM

MAXIMUM

\[ E^{t}_{rc} \]

REACTOR - CYCLE ENERGY PRODUCTION
Performing the integration of Equation (4.12), the linear approximation results in a quadratic programming (QP) problem,

\[
\text{minimize } \sum_{E_{ST}}^{t+1} = \sum \sum \left\{ \frac{\alpha_{rc}}{2} \left( (E_{rc}^{t+1})^2 - (E_{rc}^t)^2 \right) + b_{rc} (E_{rc}^{t+1} - E_{rc}^t) \right\}
\]

subject to the capacitated supply network constraints of Equations (4.13) and (4.14).

On the other hand, the stair-step approximation leads to a linear programming (LP) problem utilizing the method of "convex combinations" (54) of \(E_{rc}^t\) and \(E_{rc}^{t+1}\). In fact, since the model's context is a supply network and the objective function is linear, this special LP problem reduces to a network programming (NP) problem,

\[
\text{minimize } \sum_{E_{ST}}^{t+1} = \sum \sum \lambda_{rc} \cdot (E_{rc}^{t+1} - E_{rc}^t)
\]

Considering only the accuracy of the underlying approximations, a QP code package ought to be favored over a NP package for achieving the sub-optimization. However, even the example optimization problem of Section 4.4 (with 1200 primary variables subject to 2700 constraints), is too large for a typical generalized QP package (6) which permits only 1100 variables (including slack variables) and 800 constraints.
Investigating the stair-step approximation further by decreasing $\Delta$ and increasing the number of steps, Equation (4.66) becomes a "piecewise-linear" (54) NP problem and the second approximation approaches the first with regard to accuracy. [This piecewise-linearization refers to $\overline{TC}_r$ and is made possible by the separability of the equivalent objective function Equation (4.12)]. Furthermore, specialized NP packages tailored to capacitated networks (27, 45) are available that can readily handle up to 10,000 primary capacitated variables and up to 5000 system production-type constraints (see Appendix G). Such capabilities easily permit the additional variables introduced during the piecewise-linearization.

To illustrate a single inner iteration consider the 3 reactor, 24 period example of Figure 4.12 and Table 4.1. Figure 4.14 presents a hypothetical set of incremental cost curves returned to the SOM at the end of the previous iteration. These are taken with respect to changes about the indicated $E_{rc}^t$. Also indicated is the next trial set $E_{rc}^{t+1}$ resulting from the single inner optimization. Note that (1) the NP program seeks to establish equal nuclear incremental costs (see Section 2.4.2) among the reactor-cycles that compete for the nuclear potential (e.g., $\lambda_{1,1} = \lambda_{2,2} = \lambda_{3,1}$) and (2) the total increase in cycle energies in a given trial equals the total decrease in cycle energies in that trial since the total nuclear
Figure 4.14

Hypothetical Set of Incremental Cost Curves

\[
\begin{align*}
\lambda_{rc} & = \text{INCREMENTAL COST} \\
E_{rc} & = \text{CYCLE ENERGY (10^3 GWH)}
\end{align*}
\]

- \( \Delta \) represents \( E_{rc}^t \)
- \( \circ \) represents \( E_{rc}^{t+1} \)

\( r_c = 1.2 \)

\( E_{2.1} + 5000 \)
potential, of course, does not change from iteration to iteration. Figure 4.15 presents the complete period-by-period reactor production schedule for t+1.

4.4.3 Outer Iteration on Shape Misfit Potential

As outlined in Section 4.4 and Figure 4.11, inner cost iterations continue until the \{E_{rc}^t\} converges to \{E_{rc}^*\} at which time the outer iteration commences. The objective function \(M^{*,s}\) of the outer shape iteration is based on the key fact that if all \(l_{rp}^* = T_p^*\), then \(w_p^2 = 0\) [from Equation (4.48)]. Hence, \(v_p^2 = s_p^2\) and consequently, all periods are feasible since \(v_p^2 \gg v_{REJ}^2\) (see Figure 4.10). Furthermore, any deviation of \(l_{rp}^*\) from \(T_p^*\) increases the likelihood of ultimate period rejection.

Each outer shape iteration of Figure 4.11 thus solves the following sub-optimization problem:

\[
\text{minimize } M^{*,s}(E) \equiv \sum_{r=1}^{R} \sum_{p=1}^{P} \int_{E_{rc} \text{ corr.}}^{E_{rc}} m_{rp}(E_{rc}) dE_{rc} \quad (4.67)
\]

such that

\[
\sum_{r=1}^{R} E_{rc} = N_p \text{ for all } p \quad (4.13)
\]

\[
E_{cp}^{min,s} \leq E_{rc} \leq E_{cp}^{max,s} \text{ for all } r \text{ and } p \quad (4.14)
\]

\[
E_{rc} \equiv \sum_{p=1}^{P_{rc}} E_{rc} = E_{rc}^{*,s} \text{ for all } r \text{ and } c \quad (4.68)
\]
### Sample Reactor Production Schedule

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>REACTOR 1 CYCLE</th>
<th>REACTOR 2 CYCLE</th>
<th>REACTOR 3 CYCLE</th>
<th>NUCLEAR POTENTIAL, GWH</th>
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<td>722</td>
<td>691</td>
<td>2128</td>
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<td>720</td>
<td>652</td>
<td>2069</td>
</tr>
<tr>
<td>3</td>
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<td>721</td>
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<td>4</td>
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<td>707</td>
<td>582</td>
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</table>
The $M^*, S$ system misfit potential, defined by Equation (4.67), merely represents a mathematical "gimmick" designed to force $E$ (i.e., the set of all $E_{rcp}$) into the feasible region, minimizing the number of period shapes later rejected due to misfitting shapes [Equation (4.62)]. The all-important misfit forcing function, $m_{rp}$, though arbitrary, should possess the properties indicated in Figure 4.16. At $E_{rcp}$ corresponding to $\ell' = \ell'$, $m_{rp} = 0$; for deviations in either direction from this $E_{rcp}$, $m_{rp}$ increases rapidly; and for the end points $E_{min, rcp}$ and $E_{max, rcp}$, which are especially vulnerable to rejection, $m_{rp}$ should still be finite since the extremums are not unacceptable per se. The optimization of Equations (4.67) to (4.68) thus attempts to force each $E_{rcp}$ to the bottom of the resulting "trough" of $m_{rp}$ subject to the various constraints, such as fixed reactor-cycle energy.

Since $M^*, S$ is defined (via the $m_{rp}$) to be separable and convex, the methods of piecewise-linearization and convex combinations can again be applied as was done for the inner cost iterations of Section 4.4.2. Note that given the typical, but arbitrary stair-step $m_{rp}$ curve of Figure 4.16, the linearized $M^*, S$ optimization of the capacitated supply network is not iterative in nature--the complete optimization of $E^*, S$ occurs in one pass through the NP package. The actual "iteration" involves checking resulting period shape acceptabilities and appropriately altering the reactor production constraints for the next
Figure 4.16

Misfit Forcing Function versus Reactor-Period Production

$E_{rep}, \text{ Reactor-Period Energy Production}$

$E_{rep}$, REACTOR-PERIOD ENERGY PRODUCTION
set of inner cost iterations (see Figure 4.11).

Looking at each optimized period in turn (the notation is shortened to $E_r$ for convenience), the variance test of Equation (4.62) is applied. If $S^2 - W^2 > V^2_{\text{REJ}}$, the period is accepted and processing moves on to the next period. If the test fails, then $V^2 (\equiv S^2 - W^2) \leq V^2_{\text{REJ}}$. Defining $\sigma$ as a following measure of infeasibility,

$$
\sigma \equiv \sqrt{V^2_{\text{REJ}} - V^2} \tag{4.69}
$$

$\sigma$ represents the average change of each $l'_r$ (toward $\bar{l}'$) required before the postulated production shape would pass the test. If a fraction $\gamma$ of this average reduction is applied to each reactor's limiting values of $l'_r$ (see Figure 4.17), then from Equation (4.35),

$$
E^{\min, s+1}_r = E_{rl} + k_r T_p r \left[ (l'_r)^{\min, s} + \gamma \sigma \right] \tag{4.70}
$$

$$
E^{\max, s+1}_r = E_{rl} + k_r T_p r \left[ (l'_r)^{\max, s} - \gamma \sigma \right] \tag{4.71}
$$

When all periods have been tested thusly, and/or the appropriate limits altered, the outer shape iteration terminates and inner cost iterations begin on the new subproblem. The shape iteration which results in all period shapes being accepted, terminates the entire optimization at the feasible global optimum $E^*$ and minimum total
Figure 4.17

"Squeezing" Permissible Reactor Production Shapes

OLD: \((Q')_{MAX,s+1}\)
NEW: \((Q')_{MAX,s+1}\)

\(\gamma \sqrt{\frac{V_{REJ}}{V}} - \frac{V}{\gamma} = \gamma \sigma\)

OLD: \((Q')_{MIN,s}\)
NEW: \((Q')_{MIN,s+1}\)

\(F\), PROBABILITY \((P_e >)\)

\(P_e\), EQUIVALENT LOAD (MW) ON NUCLEAR UPPER INCREMENTS

\(k'_T\)
cost $\overline{TC}^\bullet$. [Note that if $V_{REJ}^2 \leq -0.25$ (see Section 4.2.4.3), all period shapes are acceptable regardless of feasibility. Hence, $\mathcal{E}^\star,0 = \mathcal{E}^\bullet$ and $\overline{TC}^\star,0 = \overline{TC}^\bullet$ immediately.]

4.5 Completion of Supervisory Task

With the optimization task completed, the resulting feasible optimum $\overline{TC}^\bullet$ represents the total revenue requirement for nuclear fuel $RR_N$. By present-valuing all of the other period expenditures (received as input from the SIM) according to Equation (2.17),

$$\text{ORR} = RR_N + \sum_{p} \frac{1}{(1+x)^{r_p}} \left( X_{F_p} + X_{S_p} + X_{U_p} \right) \quad (4.72)$$

The ORR operating revenue requirement is appropriately stored for later comparison with that of other possible alternative strategies. With the completion of this task, processing of the particular alternative strategy is complete. And with completion of the last alternative strategy, selection of the minimum ORR cost strategy becomes possible (see Section 2.5.1).

4.6 SYSOPT, A Computerized SYStem OPTimization Model

SYSOPT, a 2100 card Fortran IV version of the SYStem OPTimization Model is detailed in Appendix F. SYSOPT is link-edited with the Out of Kilter Network Program (45) which represents an additional 1200 cards in Fortran IV and Assembler Language. Out of Kilter is detailed in
Appendix G. This section merely summarizes the capabilities of the current combined version ofSYSOPT.

The limitations of the current version of SYSOPT, though easily altered, are as follows:

1. up to 15 reactors,
2. up to 15 cycles per reactor within the horizon,
3. up to 3 cycles per reactor beyond the horizon,
4. no limit on number of strategies per computer run and
5. up to 100 periods per strategy.

Input data for each strategy includes:

1. Present value rate,
2. Various convergence criteria,
3. Various \( \Delta \) for linearizing \( \lambda_{rc} \) of inner iterations,
4. Maximum total number of inner iterations to be permitted,
5. Number of linearized segments in \( m_{rp} \) (up to 10) and
6. \( V^2_{REJ} \) and \( \gamma \) of the shape iteration.

Input data supplied manually for each reactor includes:

1. Optional initial estimates of \( \lambda^*_{rc} \) or \( E^*_{rc} \),
2. Holdover energy at end of planning horizon, \( E_{r,c,z+1} \) and
3. Cycle energies and refueling dates beyond planning horizon.
The large volume of SYSINT output required by SYSOPT may be passed either on disk, magnetic tape or punched cards.

As for typical running times on an IBM 370 model 155 computer (MVT environment), the cases presented in Chapter 5 for a hypothetical six reactor utility required only 9 CPU seconds per inner iteration (exclusive of time spent in CORSOM's) for strategies 72 periods long and totaling 30 reactor-cycles. The SYSOPT code itself requires 130 K bytes of storage (plus ~ 26 K for computer supervisor) while the Out-of-Kilter Network Program requires an additional 135 K. Using an overlay structure reduces the 265 K total to 200 K. [When link-edited with QKCORE (see Appendix H) to complete the overall nuclear power management model (see Section 5.2), the code storage requirement increases to 345 K without overlay or 220 K with overlay (exclusive of computer supervisor).] Execution time is not noticeably increased by the use of the overlay structure.

4.7 **Summary**

For each multi-year refueling and maintenance strategy, the SOM receives period-by-period system nuclear energy production requirements and system non-nuclear operating costs. The SOM performs a two-stage iterative optimization in conjunction with the necessary CORSOM's to produce the required nuclear energy at minimum total nuclear cost. The
optimized final nuclear cost is then added to the present-value of all the other operating expenses to determine the total ORR operating revenue requirement for the strategy. It is this final total cost which is used to rank the alternatives economically.
CHAPTER 5

EVALUATION OF THE SYSTEM INTEGRATION AND OPTIMIZATION MODELS

5.1 Purpose of Evaluation: Critical Questions

When pursuing research in "methods development," important questions must be answered. These critical questions revolve around the characteristics of the numerical method and the model itself:

(1) To what problems is the model applicable?
(2) What assumptions are required?
(3) Does the method converge to an optimum?
(4) Is it the global optimum?
(5) How accurate are the results?
(6) What are the computational requirements?

Once these questions have been answered satisfactorily, research interest shifts from the methodology to the impact of its results.

Since the main thrust of the work reported here is methods development, the purpose of the evaluation is to aid and abet further development by searching for the answers to these basic questions. After a brief discussion of the hypothetical utility system studied (Section 5.3), the detailed discussion of results is presented. Section 5.8 concludes the chapter with a summary of the findings with respect to each of the critical questions.
5.2 Completion of Nuclear Power Management Multi-year Model

To properly evaluate the SIM and SOM (or more specifically, the computerized versions SYSINT and SYSOPT, respectively), requires interfacing them with a RAMM and CORSOM's to complete the nuclear power management multi-year model of Figure 2.21.

For the purposes of developing and testing a SIM and SOM, the multitude of possible alternative strategies output by a RAMM may be replaced by a few typical strategies developed through simple hand calculations (see Section 5.3.3). On the other hand, the on-line iterative nature of the optimization procedure requires computerized CORSOM's. The state of the art, as witnessed by the concurrent methods development research by Kearney (41) and Watt (55), precluded utilization of an established multi-year CORSOM. In order to proceed with the testing of the SIM and SOM, QKCORE, a pseudo-one dimensional, quick core model (performing simulation only) was developed (see Appendix H). The nature of QKCORE necessarily limited the scope of the evaluation to LWR's with the following characteristics:

(1) Modified-scatter refueling with fixed number of zones (e.g., refueling fraction was fixed at one-third),

(2) No plutonium recycle,

(3) No optional stretchout beyond reactivity-limited energy and
(4) No cycle-to-cycle optimization

(i.e., at each refueling, minimum enrichment chosen regardless of future cycles).

Nevertheless, QKCORE is a key element in the success of the SYSOPT evaluation. By generating coupled and well-behaved physics data, the resultant total costs and marginal costs passed to SYSOPT are also well-behaved. It provides all of this at a very high speed. On an IBM 370 model 155 computer, less than 15 milliseconds (CPU time) per reactor cycle were required to choose the proper refueling enrichment to yield the required cycle energy, deplete the core and calculate the cost of that energy. On the same computer, a simplified two dimensional FLARE-type model requires on the order of seconds to perform the depletion task alone—an increase of at least two orders of magnitude.

5.3 Hypothetical Utility System Studied

An 11,000 MW (~ 45% nuclear) utility was hypothesized in order to confirm the nuclear power management multi-year model's applicability to large utility systems. To properly represent scheduled downtime and, at the same time, keep computation costs within a development budget, one month was chosen as the length of each time period. Customer loads (see Section 5.3.1) were forecast for six calendar years on this monthly basis. With respect to generating equipment, the utility's forty fossil generating
units (see Section 5.3.2) were chosen so as to have a representative span of sizes and heat rates. With respect to nuclear equipment, four 1050 Mwe PWR's were assumed to be on the system initially with two more to be commissioned on specific dates within the planning horizon. These additions, plus typical fossil additions and retirements were taken as fixed for the multi-year horizon.

Assuming negligible (or invariant) transmission costs and with all alterations to system generating capacity completely specified, only the operating revenue requirements need be considered when comparing alternative refueling and maintenance strategies (see Section 2.1.3). Three such possible alternative strategies (see Section 5.3.3) were developed for satisfying the customer load demands and the generating equipment maintenance requirements.

The model's behavior for a typical strategy (see Section 5.6) and the relative economics of the three strategies (see Section 5.7) form the data base for all of the evaluations in this chapter.

5.3.1 Customer Loads

Representation of monthly customer loads required three pieces of information:

(1) a load-duration curve, normalized on both scales,
(2) a normalizing factor for the load scale (P^max_D MW peak load) and
(3) a normalizing factor for the duration scale
(T' hours in the time period)

Utilizing Commonwealth Edison data covering several recent years, the four normalized load-duration curves presented in Figure 5.1 were chosen to represent obvious seasonal variations.

A typical set of twelve monthly peaks (see Figure 5.2) was assembled for the first year with an overall peak of 10,000 MW occurring in July. The resultant monthly minimum loads are also presented in Figure 5.2. Note that what may appear at first glance in Figure 5.1 to be seasonal variations in the minimum load are actually the result of variations in the peak loads, i.e., the normalizing factors. In fact, the non-seasonal nature of the nightly minimum load components results in remarkably constant monthly minimum loads.

For the remaining five years in the planning horizon, monthly peaks (see Table 5.1) were forecast using 7% annual growth (rounded to 10 MW). As for time period duration, all months were assumed to be 730 hours (30.4 days) in length.

Having specified the required three pieces of information for each period, customer loads had been forecast six years in the future. One of the current model's shortcomings is that it assumes these are perfect forecasts, which, therefore, are treated as deterministic. The
Figure 5.1

Input Load-Duration Curves

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<tr>
<th>LOAD-DURATION CURVE NUMBER</th>
<th>MONTHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FEBRUARY, MARCH, APRIL</td>
</tr>
<tr>
<td>2</td>
<td>NOVEMBER, DECEMBER, JANUARY</td>
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<td>3</td>
<td>MAY, SEPTEMBER, OCTOBER</td>
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<td>4</td>
<td>JUNE, JULY, AUGUST</td>
</tr>
</tbody>
</table>
Figure 5.2

Forecasted Monthly Minimum and Maximum Loads for First Year

MONTHLY MAXIMUM LOADS

MONTHLY MINIMUM LOADS

LOAD-DURATION CURVE NUMBER

MONTH
<table>
<thead>
<tr>
<th>Month</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
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<td>12,250</td>
<td>13,100</td>
<td>14,000</td>
</tr>
<tr>
<td>August</td>
<td>9,750</td>
<td>10,430</td>
<td>11,170</td>
<td>11,950</td>
<td>12,780</td>
<td>13,650</td>
</tr>
<tr>
<td>September</td>
<td>8,500</td>
<td>9,100</td>
<td>9,730</td>
<td>10,410</td>
<td>11,130</td>
<td>11,900</td>
</tr>
<tr>
<td>October</td>
<td>7,600</td>
<td>8,130</td>
<td>8,700</td>
<td>9,310</td>
<td>9,960</td>
<td>10,640</td>
</tr>
<tr>
<td>November</td>
<td>7,900</td>
<td>8,450</td>
<td>9,050</td>
<td>9,680</td>
<td>10,350</td>
<td>11,070</td>
</tr>
<tr>
<td>December</td>
<td>8,200</td>
<td>8,770</td>
<td>9,400</td>
<td>10,050</td>
<td>10,740</td>
<td>11,490</td>
</tr>
</tbody>
</table>
significant probabilistic nature of the Booth-Baleriaux model derives from the simulation of each unit's stochastic forced-outages, not customer's stochastic demands. Though errors in forecasting monthly peaks can be incorporated into the model (18), the truly difficult uncertainties, such as incorrect load-duration shape, have not been adequately investigated. Research into this area is needed to establish the sensitivity of various results to such uncertainties and to develop means of incorporating them directly so that the model yields not only a numerical answer, but also a confidence interval around it.

5.3.2 Generating Equipment

Again relying on Commonwealth Edison Company data, a representative mix of fossil generating equipment was assembled (see Table 5.2). For reliability, units greater than 300 MW were considered must-run units (i.e., at least at minimum load) provided enough demand was present for the must-run units themselves.

Also presented in Table 5.2 are unit heat rate characteristics for each of the nuclear plants. Because of their size and economics, these six units are also treated as must-run units. All have high heat rates characteristic of light water reactors. The two nuclear units (E and F) under-construction at time-zero are assumed to have only 70% performance probabilities for the first twelve months of commercial service. After this shakedown period, they are
<table>
<thead>
<tr>
<th>Unit No.</th>
<th>Name</th>
<th>Rated Capacity (MW)</th>
<th>Type</th>
<th>SU-SD No.</th>
<th>Performance Probability (%)</th>
<th>Valve Point by Valve Point Heat Rate Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Capacity in MW and Heat Rate in BTU/kwh</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>K1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F</td>
</tr>
<tr>
<td>1</td>
<td>A100</td>
<td>100</td>
<td>fossil</td>
<td>510</td>
<td>0.87</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>A120</td>
<td>120</td>
<td>fossil</td>
<td>305</td>
<td>0.90</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>A120</td>
<td>120</td>
<td>fossil</td>
<td>340</td>
<td>0.91</td>
<td>35</td>
</tr>
<tr>
<td>4</td>
<td>A140</td>
<td>140</td>
<td>fossil</td>
<td>250</td>
<td>0.85</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>A140</td>
<td>140</td>
<td>fossil</td>
<td>520</td>
<td>0.94</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>C140</td>
<td>140</td>
<td>fossil</td>
<td>1050</td>
<td>0.00</td>
<td>60</td>
</tr>
<tr>
<td>7</td>
<td>A160</td>
<td>160</td>
<td>fossil</td>
<td>690</td>
<td>0.89</td>
<td>25</td>
</tr>
<tr>
<td>8</td>
<td>A160</td>
<td>160</td>
<td>fossil</td>
<td>520</td>
<td>0.87</td>
<td>35</td>
</tr>
<tr>
<td>9</td>
<td>C160</td>
<td>160</td>
<td>fossil</td>
<td>1000</td>
<td>0.00</td>
<td>45</td>
</tr>
<tr>
<td>10</td>
<td>D160</td>
<td>160</td>
<td>fossil</td>
<td>1130</td>
<td>0.90</td>
<td>45</td>
</tr>
<tr>
<td>11</td>
<td>B220</td>
<td>220</td>
<td>fossil</td>
<td>660</td>
<td>0.85</td>
<td>70</td>
</tr>
<tr>
<td>12</td>
<td>B220</td>
<td>220</td>
<td>fossil</td>
<td>640</td>
<td>0.90</td>
<td>70</td>
</tr>
<tr>
<td>13</td>
<td>C220</td>
<td>220</td>
<td>fossil</td>
<td>1450</td>
<td>0.91</td>
<td>60</td>
</tr>
<tr>
<td>14</td>
<td>D220</td>
<td>220</td>
<td>fossil</td>
<td>1460</td>
<td>0.89</td>
<td>60</td>
</tr>
<tr>
<td>15</td>
<td>A320</td>
<td>320</td>
<td>fossil</td>
<td>1750</td>
<td>0.87</td>
<td>140</td>
</tr>
<tr>
<td>16</td>
<td>B500</td>
<td>500</td>
<td>fossil</td>
<td>1360</td>
<td>0.94</td>
<td>200</td>
</tr>
<tr>
<td>17</td>
<td>A600</td>
<td>600</td>
<td>fossil</td>
<td>4160</td>
<td>0.87</td>
<td>4160</td>
</tr>
<tr>
<td>18</td>
<td>A650</td>
<td>650</td>
<td>fossil</td>
<td>3500</td>
<td>0.95</td>
<td>3500</td>
</tr>
<tr>
<td>19</td>
<td>A700</td>
<td>700</td>
<td>fossil</td>
<td>4500</td>
<td>0.95</td>
<td>4500</td>
</tr>
<tr>
<td>20</td>
<td>A830</td>
<td>830</td>
<td>fossil</td>
<td>5980</td>
<td>0.99</td>
<td>5980</td>
</tr>
<tr>
<td>21</td>
<td>A830</td>
<td>830</td>
<td>fossil</td>
<td>5920</td>
<td>0.91</td>
<td>5920</td>
</tr>
</tbody>
</table>

TABLE 5.2: GENERATING UNIT DATA
assumed to perform 95% of the time. The physics characteristics of the reactors are detailed in Appendix H.

In order to impose a more severe test of the nuclear planning ability of the model, the dispatcher's opportunities to base-load the nuclear capacity were decreased by adding an admittedly artificial constraint—a long-term contract with a neighboring utility for 1550 MW capacity with 100% guaranteed availability.

The schedule for installing and retiring utility equipment to keep pace with load growth is presented in Table 5.3. All plants not specifically mentioned exist both before and after the time span of interest. Note the typical trend of retiring smaller (and older) equipment with high heat rates in favor of larger, more efficient units. The system characteristics are summarized in Table 5.4. (The term "system resources" refers to wholly-owned capacity plus firm purchases). A typical summer and non-summer month on the hypothetical system are shown in Figures 5.3 and 5.4, respectively. The difficulty in base-loading the nuclear plants is readily apparent.

5.3.3 Maintenance and Refueling Strategies

While developing maintenance and refueling strategies, various scheduling constraints, maintenance requirements and initial conditions had to be considered. Due to summer peak loads, reliability considerations were assumed to dictate that no scheduled maintenance was to be performed during
## Table 5.3

**Additions and Retirements of Equipment**

<table>
<thead>
<tr>
<th>Year</th>
<th>First Month</th>
<th>(Period)</th>
<th>Unit Name</th>
<th>Last Month</th>
<th>(Period)</th>
<th>Unit Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Second</td>
<td>June</td>
<td>(18)</td>
<td>A-600</td>
<td></td>
<td>NONE</td>
<td></td>
</tr>
<tr>
<td>Third</td>
<td>June</td>
<td>(30)</td>
<td>A-830 PK-16</td>
<td>August</td>
<td>(32)</td>
<td>B-160</td>
</tr>
<tr>
<td>Fourth</td>
<td>June</td>
<td>(42)</td>
<td>Reactor F</td>
<td>August</td>
<td>(44)</td>
<td>A-100</td>
</tr>
<tr>
<td>Fifth</td>
<td>June</td>
<td>(54)</td>
<td>C-220 B-600 PK-17 PK-18</td>
<td>August</td>
<td>(56)</td>
<td>A-120</td>
</tr>
<tr>
<td>Sixth</td>
<td>June</td>
<td>(66)</td>
<td>D-220 B-830 PK-19</td>
<td>August</td>
<td>(68)</td>
<td>B-120</td>
</tr>
</tbody>
</table>
Table 5.4
Summary of System Characteristics

I. Customer Loads:

<table>
<thead>
<tr>
<th>Load-Duration Curves</th>
<th>See Figure 5.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly Peaks for First Year</td>
<td>See Figure 5.2</td>
</tr>
<tr>
<td>Monthly Peaks for Six Years</td>
<td>See Table 5.1</td>
</tr>
</tbody>
</table>

II. Generating Equipment:

<table>
<thead>
<tr>
<th>Unit Data</th>
<th>See Table 5.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additions and Retirements</td>
<td>See Table 5.3</td>
</tr>
</tbody>
</table>

III. Resulting System Configuration:

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Per Cent of System Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil (Non-Peaking)</td>
<td>29-36</td>
</tr>
<tr>
<td>Fast-Start Peaking</td>
<td>10-11</td>
</tr>
<tr>
<td>Nuclear</td>
<td>41-46</td>
</tr>
<tr>
<td>Firm Purchases (1550 MW)</td>
<td>11-14</td>
</tr>
<tr>
<td>Total System Resources</td>
<td>100%</td>
</tr>
<tr>
<td>Annual Peak Demand</td>
<td>88-89</td>
</tr>
<tr>
<td>Resource Margin</td>
<td>11-12%</td>
</tr>
</tbody>
</table>
Figure 5.3
Typical Summer Month (Based on July of Fourth Year)
Figure 5.4

Typical Non-Summer Month (Based on December of Fourth Year in Strategy 2)
June, July or August. This typical constraint provided a convenient way of looking at schedules—as nine month "windows" between two summers. Maintenance requirements for (non-peaking) fossil equipment were set at one month per year while fast-start peaking equipment was assumed to be maintained during off-line hours. Two months downtime was assumed for each nuclear refueling. The initial conditions of each reactor core are indicated in Table 5.5.

Within this context, the following three nuclear refueling schedules were postulated:

S-1: Strictly annual refueling
S-2: Gradual shift to longer cycles (14 months) to increase cycle energy production
S-3: Immediate shift to the longer cycles.

These schedules are presented graphically in Figures 5.5, 5.6 and 5.7, respectively. For each of these strategies, fossil maintenance was then scheduled so as to level-off the monthly capacity margin. Figures 5.8, 5.9 and 5.10 present detailed views of the maintenance and refueling schedules for each of the strategies during the first full scheduling window. Note that during the window, each strategy, in turn, refuels one less reactor (i.e., 2100 MW-months less downtime). Thus, the average monthly resource margin during the nine month window increases by 233 MW.

Before considering Strategy 3 further, note that due to the immediate shift to longer cycles, two initial conditions must be violated—namely, the enrichments already
<table>
<thead>
<tr>
<th>Reactor</th>
<th>Current Status</th>
<th>Scheduled Refueling During First Year</th>
<th>Enrichment Ordered (w/o U-235)</th>
<th>Zone</th>
<th>Current Core Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Enrich. (Fab.) (w/o U-235)</td>
<td></td>
<td>Current Burnup (MWD/Kg)</td>
</tr>
<tr>
<td>A</td>
<td>Generating</td>
<td>October-November</td>
<td>Open</td>
<td>1</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>3.3</td>
</tr>
<tr>
<td>B</td>
<td>Generating</td>
<td>February-March</td>
<td>3.4</td>
<td>1</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>3.2</td>
</tr>
<tr>
<td>C</td>
<td>Down for Refueling</td>
<td>January (Current)</td>
<td>3.6</td>
<td>1</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>N/A</td>
</tr>
<tr>
<td>D</td>
<td>Generating</td>
<td>April-May</td>
<td>3.2</td>
<td>1</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>3.2</td>
</tr>
<tr>
<td>E</td>
<td>Under-Constr.</td>
<td>Open</td>
<td>Open</td>
<td>1</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>(On-line June First year)</td>
<td></td>
<td></td>
<td>2</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>2.2</td>
</tr>
<tr>
<td>F</td>
<td>Under-Constr.</td>
<td>Open</td>
<td>Open</td>
<td>1</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>(On-line June Fourth year)</td>
<td></td>
<td></td>
<td>2</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>2.2</td>
</tr>
</tbody>
</table>
Strategy 1: Annual Refueling (12 Month Cycles = 10 Up + 2 Down)

Figure 5.5

- **ENRICHMENT LOADED AT START OF CYCLE (w/o U-235)**
- **SUMMER MONTHS**
- **TWO MONTH REFUELING***

**REACTOR**

- **A**
  - 9 MONTH IRRADIATION
  - 10

- **B**
  - 3.4 w/o
  - 10

- **C**
  - 3.6 w/o
  - 10

- **D**
  - 3.2 w/o
  - 10

- **E**
  - 3.2 w/o
  - 9

- **F**
  - 3.2 w/o
  - 15

**TIME (YEARS)**

- 0
- 1
- 2
- 3
- 4
- 5
- 6

*NOTE: Not all elements are labeled in the diagram.*
Figure 5.6

Strategy 2: Gradual Shift to Longer Cycles (14 Months when Possible = 12 Up + 2 Down)
Figure 5.7

Strategy 3: Immediate Shift to Longer Cycles (14 Months when Possible = 12 Up + 12 Down)

- Reactor A: 9 Month Irrad.
- Reactor B: 12 months
- Reactor C: 3.6 w/o 10 months
- Reactor D: 15 months
- Reactor E: 3.2 w/o 17 months
- Reactor F: 3.2 w/o 16 months

- Summer Months
- Enrichment Loaded at Start of Cycle (w/o U-235)
- Two Month Refueling

Time (Years): 0 1 2 3 4 5 6
Figure 5.8

Resource Commitment for S-1 During First Scheduling Window
Figure 5.9

Resource Commitment for S-2 During First Scheduling Window

- Total Resources
- Resource Margin at Peak Demand
- Committed Resources

Power (10^3 MW)
Figure 5.10

Resource Commitment for S-3 During First Scheduling Window

Power (10^3 MW)

TOTAL RESOURCES

S-1 COMMITTED RESOURCES

S-2 COMMITTED RESOURCES

S-3 COMMITTED RESOURCES

FOSSIL MAINT.

C's REFUELING

B's REFUELING

A's REFUELING

PEAK CUSTOMER DEMAND

FIRST YEAR

SECOND YEAR

MONTH
scheduled for Reactors B and D. [Kearney (41) noted the same infeasibility for abrupt large energy changes in the initial cycles.] These longer cycles require increased beginning-of-cycle reactivity to generate the additional energy. Because the QKCORE simulation model required constant refueling batch size for each unit throughout the horizon, the only alternative was to refuel with a higher enrichment. However, the minimum notice for changing reload enrichments is about nine months (20). In order to permit evaluation of S-3, a one million dollar penalty (roughly one year's carrying charges on the unused reload batch) was assessed for changing a batch enrichment on less than nine months notice. This raised new questions: Could S-3 pay such a penalty and still be economically attractive? How much of a penalty could it afford to pay?

The ability of the nuclear power management model to answer such "What if . . . ?" questions is but one indication of the model's versatility and usefulness as a utility management planning tool.

5.4 Remaining Parameters of Interest

In addition to the customer load demand, utility generating equipment and feasible maintenance and refueling schedules, other operating and cost information must be provided. Some of these inputs were arbitrarily fixed at reasonable values (see Table 5.6) throughout the evaluation. Other inputs were adjusted from case to case to evaluate the
Table 5.6

**Input Parameters Fixed Throughout Evaluation**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Startup-Shutdown Frequency Curve</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spinning Reserve Requirement</td>
<td>600</td>
<td>MW</td>
</tr>
<tr>
<td>Fossil Fuel Cost</td>
<td>40</td>
<td>$/MegaBTU</td>
</tr>
<tr>
<td>Peaking Fuel Cost</td>
<td>90</td>
<td>$/MegaBTU</td>
</tr>
<tr>
<td>Emergency Energy Purchase</td>
<td>10</td>
<td>$/MWH</td>
</tr>
<tr>
<td>Firm Energy Purchase</td>
<td>2</td>
<td>$/MWH</td>
</tr>
<tr>
<td>Tax Rate</td>
<td>52</td>
<td>per cent</td>
</tr>
<tr>
<td>Refueling downtime</td>
<td>2</td>
<td>months/</td>
</tr>
<tr>
<td></td>
<td></td>
<td>refueling</td>
</tr>
</tbody>
</table>

**Nuclear Data:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enrichment Feed Assay</td>
<td>0.711</td>
<td>w/o U-235</td>
</tr>
<tr>
<td>Enrichment Tails Assay</td>
<td>0.25</td>
<td>w/o U-235</td>
</tr>
<tr>
<td>Pre-Irradiation Investment Lead Time</td>
<td>0.5</td>
<td>year</td>
</tr>
<tr>
<td>Post-Irradiation Credit Lag Time</td>
<td>0.6</td>
<td>year</td>
</tr>
<tr>
<td>Delay Time From Yellowcake to UF₆</td>
<td>0.123</td>
<td>year</td>
</tr>
</tbody>
</table>

**Processing Yields:**

<table>
<thead>
<tr>
<th>Process</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion</td>
<td>0.995</td>
</tr>
<tr>
<td>Fabrication</td>
<td>0.99</td>
</tr>
<tr>
<td>Reprocessing</td>
<td>0.99</td>
</tr>
<tr>
<td>Re-conversion</td>
<td>0.995</td>
</tr>
</tbody>
</table>
model's performance (see Tables 5.7 and 5.8).

From a computational viewpoint, note that the six cases per strategy represent perturbations of only SYSOPT's input. Thus only one reference 72 period SYSINT run was required per strategy. Furthermore, because many of SYSINT's unit costs were fixed per Table 5.6, the effect of varying cost parameters could be determined by hand calculation.

5.5 Numerical Results

With all the pertinent information specified for each of the eighteen optimizations, the necessary computer runs were carried out. The revenue requirements and undiscounted energy totals up to the end of specified planning horizon are tabulated for each of the cases in subsequent sections where appropriate to the particular discussion. These tables are cross-referenced in Table 5.8 for ease in locating the results of the six cases.

In addition to these results, Appendix D also presents more detailed numerical results relative to each reactor-cycle (e.g., cycle energy, average energy cost, incremental energy cost and reload enrichment).

The discussion of the results of the cases is the subject of the remainder of this chapter.

5.6 Numerical Evaluation of an Optimized Strategy

Underlying later discussion of the choice from among several optimized strategies are the properties of the individual strategies themselves. The important numerical
Table 5.7
Nuclear Fuel Cycle Unit Costs

<table>
<thead>
<tr>
<th>Cost Component</th>
<th>Dimensions</th>
<th>Low (75% Reference)</th>
<th>Reference (12)</th>
<th>High (125% Reference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellowcake</td>
<td>$/lb U$_3$O$_8$</td>
<td>6.00</td>
<td>8.00</td>
<td>10.00</td>
</tr>
<tr>
<td>Conversion to UF$_6$</td>
<td>$/Kg U$</td>
<td>1.72</td>
<td>2.30</td>
<td>2.88</td>
</tr>
<tr>
<td>Separative Work</td>
<td>$/Kg SWU$</td>
<td>24.00</td>
<td>32.00</td>
<td>40.00</td>
</tr>
<tr>
<td>Fabrication</td>
<td>$/Kg U$</td>
<td>52.50</td>
<td>70.00</td>
<td>87.50</td>
</tr>
<tr>
<td>Ship. and Reproc.</td>
<td>$/Kg (U + Pu)$</td>
<td>26.25</td>
<td>35.00</td>
<td>43.75</td>
</tr>
<tr>
<td>Re-conversion</td>
<td>$/Kg U$</td>
<td>4.20</td>
<td>5.60</td>
<td>7.00</td>
</tr>
<tr>
<td>Pu Credit$^1$</td>
<td>$/gm. Fis. Pu</td>
<td>9.38</td>
<td>7.50</td>
<td>5.62</td>
</tr>
</tbody>
</table>

$^1$Note that since plutonium is a credit, it is changed in the opposite direction.
Table 5.8
Structure of Case Study

All three Strategies (S-1, S-2 and S-3) were optimized for each set of input parameters comprising Cases I through VI.

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Shortened Case Notation</th>
<th>Horizon Length (months)</th>
<th>Present Value Rate (%)</th>
<th>Nuclear Unit Costs</th>
<th>Shape Rej Criterion</th>
<th>For Results See</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>72M, 7%, R, O</td>
<td>72</td>
<td>7</td>
<td>Reference</td>
<td>0.0</td>
<td>Table 5.12</td>
</tr>
<tr>
<td>II</td>
<td>48M, 7%, R, N</td>
<td>48</td>
<td>7</td>
<td>Reference</td>
<td>N.A.</td>
<td>Table 5.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Table 5.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Table 5.19</td>
</tr>
<tr>
<td>III</td>
<td>48M, 0%, R, N</td>
<td>48</td>
<td>0</td>
<td>Reference</td>
<td>N.A.</td>
<td>Table 5.15</td>
</tr>
<tr>
<td>IV</td>
<td>48M, 12%, R, N</td>
<td>48</td>
<td>12</td>
<td>Reference</td>
<td>N.A.</td>
<td>Table 5.17</td>
</tr>
<tr>
<td>V</td>
<td>48M, 7%, L, N</td>
<td>48</td>
<td>7</td>
<td>Low</td>
<td>N.A.</td>
<td>Table 5.18</td>
</tr>
<tr>
<td>VI</td>
<td>48M, 7%, H, N</td>
<td>48</td>
<td>7</td>
<td>High</td>
<td>N.A.</td>
<td>Table 5.20</td>
</tr>
</tbody>
</table>

1 Refers to parameter values in next four columns.

2 See Table 5.7.

3 Per Section 4.4.3, if \( v_{	ext{REJ}}^2 < -0.25 \), all period production shapes are accepted regardless of feasibility. Thus, "N.A." represents "Not Applied."
properties are cost convergence, shape convergence, incremental costs and computational requirements. The results (see Table 5.9) of Strategy 2 in Case I (i.e., S-2 with 72 month horizon, 7% present value rate, Reference nuclear unit costs and zero rejection level) will be used for most of the discussion. However, when this strategy fails to clearly demonstrate a point under discussion, another will be utilized.

5.6.1 Convergence of Inner Cost Iterations

Starting from a relatively poor initial guess of equal energy in each cycle regardless of cycle length, the initial (s=0) shape iteration of S-2 in Case I required ten inner cost iterations to converge to $T_C^*,0$ (see Section 4.4.2 and Figure 4.11). The system nuclear fuel cost $T_C^t$ (i.e., the objective function of the optimization) for each iteration is presented in Figure 5.11. The revenue requirements and undiscounted energy for this converged solution are shown in Table 5.10.

The symbol $\Delta$ in Figure 5.11 represents the energy step size used to segment the incremental cost curves into the stair-step cost functions required by the NP optimization package (see Figure 4.13). As $\Delta$ decreases, the accuracy of the piecewise-linear representation increases as does the computational requirement. Thus, a relatively coarse piecewise fit for $\lambda_{rc}$ at large $\Delta$ was utilized for the initial iterations until either the cycle energies...
Table 5.9

Revenue Requirements and Undiscounted Energy for Accepted Global Optimum of Strategy 2 in Case I (72M, 7%, R, 0)

<table>
<thead>
<tr>
<th></th>
<th>$10^6$</th>
<th>MWH $10^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil Fuel</td>
<td>276.583</td>
<td>85.836</td>
</tr>
<tr>
<td>Startup-shutdown Cost</td>
<td>1.704</td>
<td>--</td>
</tr>
<tr>
<td>Emergency Purchases</td>
<td>0.407</td>
<td>0.048</td>
</tr>
<tr>
<td>Non-nuclear Production</td>
<td>278.964</td>
<td>85.884</td>
</tr>
<tr>
<td>Nuclear Fuel</td>
<td>297.709</td>
<td>194.077</td>
</tr>
<tr>
<td>System Production</td>
<td>576.673</td>
<td>279.961</td>
</tr>
<tr>
<td>Fixed Firm Purchase</td>
<td>133.920</td>
<td>81.468</td>
</tr>
<tr>
<td>System Total</td>
<td>710.593</td>
<td>361.429</td>
</tr>
</tbody>
</table>
Figure 5.11
Convergence of Inner Cost Iterations for Initial Shape Iteration of Strategy 2 in Case I

\[ t_{\text{INNER}}, \text{SYSTEM NUCLEAR FUEL REQUIREMENT} \ (\times 10^6 \$) \]

\[ \sum_{t+1}^{\text{ACT}} \]

Final accepted (feasible) optimum

\[ \Delta = 100 \text{ GWH} \text{ converged} \]

\[ \Delta = 20 \]

Initial optimum before shape consideration

\[ \Delta \text{ represents size of "stair-steps" used to approximate incremental cost curves} \]
Table 5.10
Revenue Requirements and Discounted Energy For
Converged Initial\(^1\) Shape Iteration of Strategy 2
in Case I (72M, 7\%, R,0)

<table>
<thead>
<tr>
<th></th>
<th>$ 10^6$</th>
<th>MWH 10^6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil Fuel</td>
<td>276.853</td>
<td>85.836</td>
</tr>
<tr>
<td>Startup-shutdown Cost</td>
<td>1.704</td>
<td>--</td>
</tr>
<tr>
<td>Emergency Purchases</td>
<td>0.407</td>
<td>0.048</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-nuclear Production</td>
<td>278.964</td>
<td>85.884</td>
</tr>
<tr>
<td>Nuclear Fuel</td>
<td>297.456</td>
<td>194.077</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Production</td>
<td>576.420</td>
<td>279.961</td>
</tr>
<tr>
<td>Fixed Firm Purchase</td>
<td>133.920</td>
<td>81.468</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Total</td>
<td>710.340</td>
<td>361.429</td>
</tr>
</tbody>
</table>

\(^1\)Per Section 4.4.3, these results also apply for the global optimum for the following input set: 72M, 7\%, R, N (cf. Table 5.8).
converged (to within a specified per cent of \( \Delta \), typically 100\%) or the objective function itself converged (i.e., \( \sum_{ST}^{t+1} \) of the last iteration failed to improve the objective function by more than a required amount, say $2000). In fact, iteration 5 displayed "negative" improvement because piecewise-linearization of \( TC_r \) prevented the NP program from seeing the smooth increase of \( \lambda_{rc} \) for fractional \( \Delta \) changes in cycle energy. The net result was that the NP program over-reacted to small differences between the incremental costs \( \lambda_{rc} \).

After convergence using the first \( \Delta \), a second and smaller \( \Delta \) was utilized and convergence again attained using the same two criteria. This second converged solution was considered to be the inner optimum \( TC^*,0 \).

From three standpoints, a third \( \Delta \) choice appeared unwarranted:

1. With the total nuclear fuel revenue requirement approaching $300,000,000, the fuel cost improvement from the \( \Delta = 100 \) GWH optimum solution to \( \Delta = 20 \) was only $220,000 for the fivefold \( \Delta \) reduction and would undoubtedly have been much less than that for another fivefold reduction.

2. At \( \Delta = 20 \) GWH, cycle energies were already converged to well within 1\% (\( \pm 50 \) GWH out of 6000-8000 GWH), and
(3) The fuel cost errors and cycle energy errors both appear to be well within the noise levels of CORSOM errors [> $100,000 per reactor over five years (55)] and the errors inherent in forecasting load demands and availabilities (> 1%).

Using the above sequence of the two step sizes for all cases, the initial shape iteration was effectively converged (i.e., objective function decreasing insignificantly for $\Delta = 20$ GWH) within ten inner iterations. In as much as completed CORSOM's are estimated to require over 3 minutes of IBM 370 model 155 CPU time per reactor strategy per iteration (41), a six reactor-ten iteration solution would involve over 3 hours of computer time for the CORSOM's alone. (The ad hoc simulator QKCORE required less than 3 minutes for all ten iterations.) Since each iteration of the SOM [using roughly 9 seconds (see Section 4.6)] involves another 20 minutes of CORSOM time, further investigation is recommended into improving the SOM's NP convergence and decreasing the number of iterations required.

Returning to Figure 5.11, a detailed analysis of the iteration-to-iteration improvement in the objective function is warranted. Recalling the development of the cost objective function $\Sigma_{E_{ST}}^{t+1}$ in Section 4.2.1, Equation (4.8) stated that
\[
\overline{TC}^{t+1} = \overline{TC}^t + \delta^{t+1} + \sum \sum \frac{E_{rc}^{t+1}}{E_{rc}^t} \lambda_{rc}^t \ dE_{rc}^{t+1}
\]

Since,

\[
\overline{TC}^{t+1} = \overline{TC}^t + \sum_{ACT}^{t+1} = \overline{TC}^t + \delta^{t+1} + \sum_{EST}^{t+1}
\]

Therefore,

\[
\delta^{t+1} = \sum_{ACT}^{t+1} - \sum_{EST}^{t+1}
\]

Both \( \sum_{EST}^{t+1} \) and \( \delta^{t+1} \) are presented in Figure 5.12.

Section 4.2.1 postulated simplification of the objective function [Equation (4.12)] based on the assumption that the resulting error \( \delta^{t+1} \) was much less than the projected improvement, which is the case seven out of nine times. The two failures are a combination of (1) the actual error in the simplification and (2) the NP program's over-reaction to small differences in incremental costs.

By plotting \( \delta^{t+1} \) versus the average (root-mean-square) energy change for all reactor-cycles altered between the two iterations, Figure 5.13 results. Intuitively, such behavior was to be expected—namely, \( \delta^{t+1} \) tends to grow large for large shifts in energy. The cluster of data representing less than
Figure 5.12
Change in Total Nuclear Fuel Cost During Inner Iterations of Initial Shape Iteration of Strategy 2 in Case 1

\[ \delta^{t+1} = \text{Error in Estimate} = \Sigma^{t+1}_{ACT} - \Sigma^{t+1}_{EST} \]

Estimation improvement in total nuclear fuel cost from iteration-to-iteration.
Figure 5.13
Error in Estimated Improvements versus Change in Cycle Energies
(Strategy 2 in Case 1)

OBSERVED UPPER LIMIT
$30,000 errors for changes on the order of 50 GWH provides adequate justification that the assumption in Chapter 4 can be applied for small changes in energy. The fact that even the largest $\delta^{t+1}$ still permits a net improvement indicates, though somewhat less convincingly, an even larger range of applicability.

In summary, the validity of the $\delta^{t+1}$ assumption of Section 4.2.1 has been established. The inner NP optimization based on it converged adequately with regard to both cycle energies and total system nuclear fuel cost. However, as previously mentioned, the rate of convergence left something to be desired.

5.6.2 Convergence of Outer Shape Iterations

Strategy 2 in Case I ($72M, 7\%, R, 0$) required four outer shape iterations to achieve the acceptable optimum TC by the method described in Section 4.4.3 using the "stairstep" $m_{rp}$ of Figure 4.16. Figure 5.14 plots the progress at each outer shape iteration of $TC^{*,s}$ and the number of rejected periods versus the average rejected $V_{p}^2$. Convergence is rapid in the sense that the early iterations greatly reduce the average $V_{p}^2$ while the later iterations reduce the number of periods that must be included in the average.

Also presented in Figure 5.14 are similar data provided by a separate computer run in which the $V_{REJ}^2$ was raised from 0.00 to 0.01. Table 5.11 presents a summary of the
Figure 5.14

Outer Shape Iteration Convergence

(STRATEGY 2 IN CASE 1)

NUMBER OF REJECTED PERIODS x 10

$V^2_{REJ} = 0.01$

ADDITIONAL COST

$V^2_{REJ} = 0.0$

ADDITIONAL COST

$T^*_C - T^*_C^0$ (10^3$) OR NUMBER OF REJECTED PERIODS ($\times 10$)

($\bar{V}^2_p$) REJECTED PERIODS
Table 5.11

Results at End of Outer Shape Iterations
(Strategy 2 in Case I)

<table>
<thead>
<tr>
<th>s</th>
<th>( TC^*, s ) (10^3$)</th>
<th>Lowest ( V^2 ) (x10^3)</th>
<th>Average Rejected ( V^2 ) (x10^3)</th>
<th>Number of Periods Rejected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>297,457</td>
<td>-12.31</td>
<td>-8.66</td>
<td>29</td>
</tr>
<tr>
<td>1</td>
<td>297,627</td>
<td>-4.03</td>
<td>-2.35</td>
<td>22</td>
</tr>
<tr>
<td>2</td>
<td>297,701</td>
<td>-4.15</td>
<td>-1.50</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>297,709</td>
<td>+0.09</td>
<td>0.0</td>
<td>0</td>
</tr>
</tbody>
</table>

\( V^2_{REJ} = 0.0 \)  
\( V^2_{REJ} = 0.01 \)
important results at the end of each shape iteration for both runs.

During the outer iterations, reactor production limits of each rejected period are "squeezed" toward each other to decrease the likelihood of further rejection (See Section 4.4.3 and Figure 4.17). When the final iteration reaches the global optimum, a distribution of the $Z = 72$ periods versus the percent original energy range remaining can be plotted as in Figure 5.15. For the run with $V_{\text{REJ}}^2 = 0$, 42 of the 72 periods required no reduction in energy range (i.e., 100% remaining since never rejected) and the maximum reduction for any single period was 22% (78% remaining). The much stiffer requirements imposed by $V_{\text{REJ}}^2 = 0.01$ ($S_p^2$ was only $\sim 0.02$), resulted in only 3 unaltered periods and 45 periods with reductions of 25% or more.

As for the proper choice of $V_{\text{REJ}}^2$ itself, Figures 5.16 to 5.18 present system and average reactor shapes yielding the indicated values of $S_p^2$ and $V_p^2$. Visual inspection indicates the infeasibility of Figure 5.16 and the acceptability of the other two periods. Furthermore, the system shape itself is not an ironclad constraint from the standpoint that the information it contains is the result of many forecasts (customer load-duration shape and performance probabilities), not of well-defined engineering constraints such as are found in deterministic optimization problems (e.g., optimum heat exchanger design). The net result is a
Figure 5.15. Distribution of 72 Period Energy Ranges Remaining at Accepted Optimum (Strategy 2 in Case I)
Figure 5.16

Typical Period with Infeasible Postulated Average Reactor Shape ($V^2 < 0$)

$F_r$ AVERAGE REACTOR SHAPE

$V_p^2 = 0.0489$

$F_e$ SYSTEM SHAPE

$S_p^2 = 0.0264$

INFEASIBLE BY EQ. (4.60)

Since $V_p^2 = -0.0225$

NUCLEAR MINIMUMS

NUCLEAR INCREMENTS

$F_e$, PROBABILITY ($P_e \geq$)

$P_e$, NUCLEAR EQUIVALENT LOAD ($10^3$ MW)
Figure 5.17

Typical Period Giving Shape Test $V_p^2$ Near Zero

$F_r$ AVERAGE REACTOR SHAPE
$W_p^2 = 0.0268$

$F_e$ SYSTEM SHAPE
$s_p^2 = 0.0284$

$V_p^2 = 0.0016$

$P_e$, NUCLEAR EQUIVALENT LOAD ($10^3$ MW)
Figure 5.18

Typical Period Giving Shape Test \( \frac{V^2}{P} \) Much Greater than Zero

\[ F_r \] AVERAGE REACTOR SHAPE
\[ \frac{V^2}{P} = 0.0052 \]

\[ F_e \] SYSTEM SHAPE
\[ \frac{V^2}{P} = 0.0137 \]

\[ \frac{V^2}{P} = 0.0189 \]

\( F_e, \) PROBABILITY (\( P_e \geq \))

\( P_e, \) NUCLEAR EQUIVALENT LOAD (\( 10^3 \) MW)

NUCLEAR MINIMUMS

NUCLEAR INCREMENTS

REACTOR A DOWN

REACTOR F UNDER-CONSTR.
recommendation that $V_{REJ}^2 = 0$ is satisfactory for planning purposes.

Figure 5.19 presents the iterative progress of $\overline{TC}^{*,s}$ for Strategy 2 in Case I versus the lowest $V^2_p$ (i.e., $V^2_p$, for the period failing the criterion by the largest amount or equivalently, the $V_{REJ}^2$ that would have accepted all periods). Since both solid curves begin from the same point, but are not co-linear, $\overline{TC}^{*,s}$ is only valid as a measure of minimum system nuclear cost at the final optimum $\overline{TC}^*$ for each $V_{REJ}^2$. In other words, the outer iterations reach their respective global optimums by a sequence of non-optimum iterations. The means of increasing the rate of outer shape convergence, as with inner cost convergence, lies merely in increasing the number of steps used in the piecewise-linearization of the objective functions.

Another input parameter affecting the outer shape iterations is the fraction $\gamma$ of the $\sigma (\equiv \sqrt{V_{REJ}^2 - V^2})$ actually applied to the reactor production limits [Equations (4.70) and (4.71)]. Figure 5.20 presents a plot of all three optimizations in Case I ($V_{REJ}^2 = 0$) as a function of the $\gamma$ used to achieve the global optimization. The ordinate represents the increase of $\overline{TC}^*$ over $\overline{TC}^*,0$, absolute minimum cost when all shape constraints are ignored (i.e., ignoring feasibility). (The revenue requirements and undiscounted energy totals for Case I are presented in Table 5.12.)
Figure 5.19
Strategy Cost versus $V_{\text{REJ}}^2$ (Strategy 2 in Case 1)
Figure 5.20
Accepted Optimum for Case I versus $\gamma$ Correction Factor

CASE I
($V_{REJ}^2 = 0.0$)

RESULT OF OVER-CORRECTING REJECTED PERIODS

STRATEGY COST PENALTY ON $\bar{T}_C^* - 0$

STRATEGY 1

STRATEGY 2

STRATEGY 3

FINAL OPTIMUM - FIRST OUTER ITERATION

$\bar{T}_C - \bar{T}_C^*$

(10^3 $)$
TABLE 5.12
REVENUE REQUIREMENTS AND UNDISCOUNTED ENERGY FOR CASE I
(72 Month Horizon, 7% P.V. Rate, Reference Nuclear Unit Costs, 0.0 Shape Rejection Criterion)
Direct Calculation Using $\gamma = 0.25$

<table>
<thead>
<tr>
<th>Strategy</th>
<th>S-1</th>
<th>S-2</th>
<th>S-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downtime to horizon (reactor-months)</td>
<td>62</td>
<td>51</td>
<td>49</td>
</tr>
<tr>
<td>Average cycle length (months)</td>
<td>12</td>
<td>14.9</td>
<td>15.2</td>
</tr>
<tr>
<td>System nuclear capacity factor</td>
<td>0.642</td>
<td>0.656</td>
<td>0.658</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>S-1 10^6$</th>
<th>S-2 10^6$</th>
<th>S-3 10^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuel</td>
<td>293.205</td>
<td>276.853</td>
<td>274.082</td>
</tr>
<tr>
<td></td>
<td>(90.068)</td>
<td>(85.836)</td>
<td>(85.196)</td>
</tr>
<tr>
<td>Startup-shutdown cost</td>
<td>2.022</td>
<td>1.704</td>
<td>1.650</td>
</tr>
<tr>
<td>Emergency purchases</td>
<td>0.655</td>
<td>0.407</td>
<td>0.363</td>
</tr>
<tr>
<td></td>
<td>(0.079)</td>
<td>(0.048)</td>
<td>(0.043)</td>
</tr>
<tr>
<td>Nonnuclear production</td>
<td>295.882</td>
<td>278.964</td>
<td>276.095</td>
</tr>
<tr>
<td></td>
<td>(90.147)</td>
<td>(85.884)</td>
<td>(85.239)</td>
</tr>
<tr>
<td>Nuclear fuel</td>
<td>294.690</td>
<td>297.709</td>
<td>300.137</td>
</tr>
<tr>
<td></td>
<td>(189.814)</td>
<td>(194.077)</td>
<td>(194.722)</td>
</tr>
<tr>
<td>System production</td>
<td>590.572</td>
<td>576.673</td>
<td>576.232</td>
</tr>
<tr>
<td></td>
<td>(279.961)</td>
<td>(279.961)</td>
<td>(279.961)</td>
</tr>
<tr>
<td>Fixed firm purchase</td>
<td>133.920</td>
<td>133.920</td>
<td>133.920</td>
</tr>
<tr>
<td></td>
<td>(81.468)</td>
<td>(81.468)</td>
<td>(81.468)</td>
</tr>
<tr>
<td>Penalty for short notice enrichment changes</td>
<td></td>
<td></td>
<td>2.000</td>
</tr>
<tr>
<td>System Total</td>
<td>724.492</td>
<td>710.593</td>
<td>712.152</td>
</tr>
<tr>
<td></td>
<td>(361.429)</td>
<td>(361.429)</td>
<td>(361.429)</td>
</tr>
</tbody>
</table>
Two points are worthy of note. First, $\gamma = 0.1$ to 0.3 appears optimal since for $\gamma$ smaller, a larger number of outer iterations (>10) would be required (i.e., slower convergence) while for $\gamma$ larger, the method over-corrects the offending periods causing an additional cost penalty. Secondly, for scoping purposes only (i.e., when only ORR is required for the comparison of many strategies and the feasibility of $E^*$ is not important for actual production purposes), the additional computations required in attaining an acceptable optimum for each and every run may not be required. (However, if the convergence of SYSOPT is accelerated, the additional shape computations may be easily tolerated in the first place.) Since the strategy versus strategy "cost of feasibility" differences are small (<$100,000$ for S-3 vs. S-2) relative to overall cost differences (~$1,400,000$), a single benchmark run is sufficient for determining the appropriate strategy cost penalty. Adding this to each $TC^{*,0}$ eliminates the need for any further outer shape iterations (for scoping purposes only).

The results of Cases II through VI presented in Section 5.7 represent such $TC^{*,0}$ solutions (i.e., ignoring all shape considerations). By applying the cost penalties indicated in Figure 5.20, they can be approximately converted to $TC^*$ (however, $E^{*,0} \neq E^*$ ).
5.6.3 Comparison of Theory and Result: Incremental Costs

The analytical discussion of utility system optimization in Section 2.4.2 presented two conclusions:

**Conclusion I:** The strong conclusion [Equation (2.70)]
that all reactor-cycles generating energy
during the same time period should be designed
at the same incremental cost, and

**Conclusion II:** The weak conclusion [Equation (2.71)]
that all reactor-cycles should simultaneously
be designed at the same incremental cost.

Recall that "strong" and "weak" refer to the number of incremental cost violations anticipated because of over-riding engineering and time constraints.

The $\lambda^{r}_{rc}$ cycle-by-cycle incremental costs at the optimum of Strategy 2 in Case I are presented in Figure 5.21. In analyzing these values, four important points are to be made. First, the general equality of $\lambda^{r}_{rc}$ at each point in time confirms Conclusion I that

$$\lambda^{r}_{N_p} = \left(\frac{\partial TC}{\partial E_{rc}}\right)_{r} = \text{constant for all } r \text{ at each } p$$

(5.4)

Secondly, incremental costs increase over the first few cycles as the short-range incremental costs of the first year give way to the mid-range incremental costs of later cycles. During the first year, incremental costs are very low because a large proportion of each reactor's cycle costs
Figure 5.21
Incremental Costs and Cycle Energies at Accepted Global Optimum
for Strategy 2 in Case 1

$C_{RC} \$/MWH

(\Phi_{RC} \text{GWH})
(e.g., separative work, fabrication and reprocessing) are already spent or committed. Discharge burnup is the only variable. Thus, $\lambda_{rl}^*$ is Widmer's short-range incremental cost (57, 59). For a cycle further into the future, a larger degree of flexibility is available in the design of the reload batch (size and enrichment) and a larger fraction of total cycle costs can thus be altered. For $c > 2$, $\lambda_{rc}^*$ becomes Widmer's mid-range incremental cost (57, 58). Thus, short-range incremental costs evolve into mid-range incremental costs.

During the middle two to five years of Strategy 2 (see Figure 5.21), the constancy of $\lambda_{rc}^*$ for most reactor-cycles provides ample evidence that Conclusion II is also valid.

Finally, the $\lambda_{rc}^*$ beyond the fifth year are optimal (but erratic) for the fixed horizon end condition of Section 4.2.3.2. Further investigation into the ideal end condition for each reactor and each strategy are recommended.

Though Figure 5.21 confirmed Conclusion II, the typical $\lambda_{rc}^*$ optima of the other strategies did not. For example, Figure 5.22 presents $\lambda_{rc}^*$ for Strategy 1 in Case I. Though Conclusion I continues to be valid with few violations, the results do not support Conclusion II.
Figure 5.22

Incremental Costs and Cycle Energies at Accepted Global Optimum for Strategy 1 in Case I

<table>
<thead>
<tr>
<th>REACTOR</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.683</td>
<td>0.992</td>
<td>1.240</td>
<td>1.063</td>
<td>0.921</td>
<td>1.096</td>
<td>1.182</td>
</tr>
<tr>
<td></td>
<td>(5280)</td>
<td>(5662)</td>
<td>(5688)</td>
<td>(5799)</td>
<td>(5760)</td>
<td>(5746)</td>
<td>(5950)</td>
</tr>
<tr>
<td>B</td>
<td>0.683</td>
<td>0.992</td>
<td>1.240</td>
<td>0.963</td>
<td>0.921</td>
<td>1.096</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(6418)</td>
<td>(6440)</td>
<td>(6240)</td>
<td>(6230)</td>
<td>(6180)</td>
<td>(6500)</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.683</td>
<td>0.992</td>
<td>1.240</td>
<td>1.031</td>
<td>0.921</td>
<td>1.096</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(6180)</td>
<td>(6140)</td>
<td>(5760)</td>
<td>(5740)</td>
<td>(5720)</td>
<td>(5656)</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>0.683</td>
<td>0.992</td>
<td>1.240</td>
<td>0.963</td>
<td>0.921</td>
<td>1.096</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(5920)</td>
<td>(6060)</td>
<td>(6400)</td>
<td>(6149)</td>
<td>(5983)</td>
<td>(6120)</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>0.683</td>
<td>0.992</td>
<td>1.689</td>
<td>1.031</td>
<td>0.846</td>
<td>1.122</td>
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<td>(3297)</td>
<td>(5337)</td>
<td>(5089)</td>
<td>(5080)</td>
<td>(6869)</td>
<td>(5326)</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.448</td>
<td></td>
<td></td>
<td></td>
<td>0.818</td>
<td>1.093</td>
<td>1.130</td>
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<td></td>
<td>(2129)</td>
<td></td>
<td></td>
<td></td>
<td>(7874)</td>
<td>(6372)</td>
<td>(5882)</td>
</tr>
</tbody>
</table>

TIME (YEARS)
Underlying any discussion of incremental costs is the source of those costs—the CORSOM, or specifically, the QKCORE in-core simulator developed merely to test the SOM. By foregoing an internal optimization, QKCORE is unable to see some obvious means of saving money. For instance, reactor-cycle E-3 of Figure 5.22 has a very high incremental cost due to energy production requiring 4% enriched reload fuel (see Appendix D, Table D.8). Yet, the previous cycle loaded the minimum enrichment allowed (1.5%). If QKCORE allowed early shutdown (reactivity > 0) and optimized the enrichments alone, it might well have loaded 2.5% fuel in E-2, burned only part of the way down and then loaded 3.0% fuel for a complete burn. Indeed, a full-scale CORSOM should be able to optimize reload batch size, as well. The development and incorporation of more versatile CORSOM's is a prerequisite to completing a fully operational nuclear power management model as in Figure 2.21.

Each inconsistency in incremental costs as cycles begin and end, can be translated directly into the optimal loading order (see Figure 5.22). During reactor-cycle E-3 (with $\lambda_{E,3} = 1.689 \$/MWH), Reactor E is loaded only after all other nuclear units (with $\lambda_{rc} = 1.240 \$/MWH) are fully loaded. Since E-3 is always loaded last, it generates $E_{E,3}^{\text{min}}$ during each included period of cycle 3 and, hence, $E_{E,3}^{\text{min}} = E_{E,3}^{\text{min}}$. As Figure 5.23 illustrates, this lower limit on cycle energy prevents E-3 from reaching the cost parity
Figure 5.23

Lower Limit on Cycle Energy Preventing Incremental Cost Parity

\[ E_{E,3} \text{ CYCLE ENERGY (10}^3 \text{ GWH)} \]

\[ \lambda_{E,3} \text{ INCREMENTAL COST ($/MWH)} \]

\[ \lambda_{E,3}^{\circ} = 1.689 \$/MWH \]

\[ 1.240 \$/MWH \text{ OF OTHER REACTORS} \]

\[ \text{INCREMENTAL COST PARITY AT 1.240 \$/MWH} \]
of Conclusion I. (If \( E_{E,3} \) was less than \( E_{E,3}^{\min} \), obviously uneconomic fossil energy costing over 2 $/MWH would be substituted for its 1.7 $/MWH energy.)

Reactor-cycle F-1 of Figure 5.22 fails to establish cost parity for the opposite reason. With the initial core configuration assumed fixed, \( \lambda^{\bullet}_{F,1} \) is a cheap (0.818 $/MWH) short-range incremental cost. (Cycle burnup is the only design variable.) Thus, Reactor F is always loaded first, generating \( E_{F,1}^{\max} \) for the cycle. As Figure 5.24 indicates, this upper limit on cycle energy can also prevent incremental cost parity.

The other \( \lambda^{\bullet}_{rc} \) inconsistencies of Figures 5.21 and 5.22 are merely more complicated versions of these two simple cases--reactor-cycles E-3 and F-1. In each instance, the optimal economic period loading order is easily deduced: cheapest first.

Comparing all reactor-cycles of Figures 5.21 and 5.22, \( \lambda_{rc} \) is seldom greater than 1.41 $/MWH. This observed upper limit on the mid-range incremental cost of nuclear power for an optimized utility system is typical of the individual reactor incremental costs observed by others (41, 55, 57, 58), especially since the Reference nuclear unit cost set (12) is also representative of typical "current" economic parameters.

As Figures 5.3 and 5.4 pointed out, base-loading of the hypothetical utility system's six nuclear reactors is
Figure 5.24

Upper Limit on Cycle Energy Preventing Incremental Cost Parity

\[ E_{F,1} \text{ CYCLE ENERGY (10}^3 \text{ GWH)} \]

\[ \lambda_{F,1} \text{ INCREMENTAL COST ($/MWH)} \]

Parity at 1.031 $/MWH

Parity at 0.963 $/MWH

Constrained Optimum

\[ E_{F,1} \]

\[ E_{F,1} \leq E_{F,1} \leq E_{F,1}^{\text{MAX}} \]

(Qualitative Only)
impossible because the utility's minimum load is too low. However, since $\lambda_N$ is always much less than $\lambda_F$ (>2.0 $/\text{MWH}$), two possibilities exist for economically utilizing the excess nuclear capacity during the low load periods to decrease system operating revenue requirements. One alternative is to sell excess nuclear capacity (i.e., energy) to neighboring utilities at any price greater than its incremental cost. Incorporation of such nuclear economy interchange sales into the SIM and SOM is recommended since this may well become a common utility practice.

The second option is to use the excess capacity on the utility's own system by operating a pumped-hydro station (see Section 2.2.3). By pumping during low load hours, $\lambda_P = \lambda_N \leq 1.4 $/MWH. Using the stored energy for peak-shaving high cost fossil the next day, $\lambda_G = \lambda_F > \sim 4 $/MWH. With overall pumped-hydro efficiency typically 67%, total operating revenue requirements are reduced roughly 2 $/\text{MWH}$ (i.e., 50% of $\lambda_F$) for each fossil MWH displaced [Equation (2.29)]. Since such a station is also comparatively cheap to install (See Table 2.1), a pumped-hydro station on the grid of a utility unable to base-load its nuclear capacity produces startling economies (21, 35). "From a utility's viewpoint, pumped storage is a natural fit with large base-load plants. It can take on load instantly, it uses off-peak power to replenish its resources, and its reliability is second to none [5]."
As pumped-hydro stations become more numerous (334 MW installed versus over 8000 MW under construction in entire United States at end of 1972 (5)], the appropriate planning tools must be developed. Thus, it is highly recommended that pumped-hydro units (and hydro units, as well) be incorporated into the SIM.

5.6.4 Computational Requirements

The computational requirements of SYSINT are detailed in Section 3.6 and Appendix E, while SYSOPT details can be found in Section 4.6 and Appendices F and G. However, Table 5.13 presents a summary of computer usage for Strategy 2 in Case I.

5.7 Evaluation of Competing Strategies

Having discussed the properties of a single optimized strategy, it now becomes appropriate to discuss the broader question of strategy versus strategy comparison. In particular, given the same set of input data (i.e., forecasts), which of the individually optimized strategies represents the optimum plan for operating the utility system? How sensitive is this choice to various parameters in the input? To answer these questions, first the results for Case II will be presented in Section 5.7.1. Later sections will then discuss the other Cases and the optimum strategy choice with respect to horizon length (Section 5.7.2), present value rate (Section 5.7.3), nuclear unit costs
Table 5.13

Computational Requirements For
Strategy 2 in Case 1

(Based on IBM 370 model 155 computer operating in
MVT environment)

<table>
<thead>
<tr>
<th>Program</th>
<th>Total Core Storage (Bytes)</th>
<th>CPU Time</th>
<th>Input/Output Time</th>
<th>Time Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>SYSINT</td>
<td>134 K</td>
<td>2.2</td>
<td>0.5</td>
<td>Sec/period</td>
</tr>
<tr>
<td>SYSOPT</td>
<td>246 K with overlay</td>
<td>9</td>
<td>7</td>
<td>Sec/inner iteration</td>
</tr>
<tr>
<td>QKCORE</td>
<td>371 K without overlay</td>
<td>13</td>
<td>&lt;1</td>
<td>Sec/inner iteration</td>
</tr>
</tbody>
</table>
(Section 5.7.4) and non-nuclear unit costs (Section 5.7.5).

5.7.1 Comparing Strategies in a Single Case

The optimized results for the three strategies (S-1, S-2 and S-3) in Case II are presented in Table 5.14. Recall from Section 5.3.3 that S-1 is an annual refueling strategy, S-2 a gradual shift to longer cycles and S-3 an immediate shift to longer cycles.

Of prime importance in correlating the results, is the refueling downtime of each strategy. Naturally, the more rapid the shift to longer cycle lengths, the fewer refuelings that must be scheduled.

With less nuclear downtime, the nuclear energy production increases and fossil energy production decreases by approximately the same amount. Also, startup-shutdown cost is decreased as the fossil units move farther away from nightly shutdown. Fewer emergency energy purchases are required due to increased on-line resource margins (see Section 5.3.3).

All three components of non-nuclear production cost thus favor reducing downtime. (By looking at the differences in non-nuclear production cost, average long-term levelized replacement energy costs of 5.2-5.7 $/MWH can be calculated.)

As mentioned above, each succeeding strategy is able to increase production because of less refueling downtime. However, the cost of this energy does not increase
### TABLE 5.14
REVENUE REQUIREMENTS AND UNDISCOUNTED ENERGY FOR CASE II
(48 Month Horizon, 7% P.V. Rate, Reference Nuclear Unit Costs, No Shape Constraints)

<table>
<thead>
<tr>
<th>Strategy</th>
<th>S-1</th>
<th>S-2</th>
<th>S-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downtime to horizon (reactor-months)</td>
<td>38</td>
<td>33</td>
<td>31</td>
</tr>
<tr>
<td>Average cycle length (months)</td>
<td>12</td>
<td>14.5</td>
<td>15.2</td>
</tr>
<tr>
<td>System nuclear capacity factor</td>
<td>0.638</td>
<td>0.647</td>
<td>0.651</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>10^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(10^6 MWH)</td>
</tr>
<tr>
<td>Fossil fuel</td>
<td>184.223</td>
</tr>
<tr>
<td></td>
<td>(51.703)</td>
</tr>
<tr>
<td>Startup-shutdown cost</td>
<td>1.497</td>
</tr>
<tr>
<td>Emergency purchases</td>
<td>0.464</td>
</tr>
<tr>
<td></td>
<td>(0.053)</td>
</tr>
<tr>
<td>Nonnuclear production</td>
<td>186.184</td>
</tr>
<tr>
<td></td>
<td>(51.756)</td>
</tr>
<tr>
<td>Nuclear fuel</td>
<td>198.267</td>
</tr>
<tr>
<td></td>
<td>(118.376)</td>
</tr>
<tr>
<td>System production</td>
<td>384.451</td>
</tr>
<tr>
<td></td>
<td>(170.132)</td>
</tr>
<tr>
<td>Fixed firm purchase</td>
<td>95.166</td>
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<td></td>
<td>(54.312)</td>
</tr>
<tr>
<td>Penalty for short-notice enrichment changes</td>
<td></td>
</tr>
<tr>
<td>System Total</td>
<td>479.617</td>
</tr>
<tr>
<td></td>
<td>(224.444)</td>
</tr>
</tbody>
</table>
proportionally. In fact, compared to S-1, S-2 generates more nuclear energy for less money! To explain this anomaly, consider the following:

(1) Less downtime means fewer reloads must be purchased.

(2) Increased average cycle length, means increased cycle energy and reload enrichment.

(3) Even with increased batch enrichment cost, the savings due to foregone reloads and the increased energy for amortizing fixed costs, etc., result in a 1.9% decrease in levelized nuclear fuel costs over the four year horizon.

(4) Due to fixed initial conditions and only gradual shift to longer cycles, S-1 and S-2 are very similar in nuclear energy production during the first year. At the end of four years, nuclear production by S-2 is only 1.4% higher. (For longer horizons, the first year matters less and nuclear energy production differences are greater.)

(5) Finally, since the levelized nuclear fuel cost decreases percentagewise more than nuclear production increases, the net result is more nuclear energy for less money.

Turning to S-3, the immediate shift to longer cycles results not only in increased energy production, but also in increased levelized fuel cost. The result is a return to normalcy--more nuclear energy costs more.
Looking then at system production cost over the 48 month horizon, S-3 saves $570,000 over S-2 and roughly ten million dollars over S-1. This, of course, is not enough to absorb S-3's assumed additional two million dollars in penalties for the two short-notice enrichment changes. Thus, among the three strategies, S-2 has minimum total system cost.

During the first four years, then, S-2's gradual shift to longer cycles saves 9.3 million dollars compared to the annual cycles of S-1. Such a savings would clearly justify a few hundred thousand dollars necessary to implement the engineering design changes in the reload fuel specifications. In fact, the savings is large enough to perpetuate S-1's poor showing in all six Cases of the input parameters (see Table 5.8 and Appendix D). (Strategy 2 is always cheaper by at least 6.7 million dollars.)

However, S-2 and S-3 are roughly competitive depending on the magnitude of the enrichment change penalty. Without the penalty S-3 is favored by roughly $600,000.\(^1\) But after the 2 million dollar penalty, it is 1.4 million dollars more costly. This competitiveness is used to advantage in the following sections where the sensitivity study is presented as a comparison of S-2 vs. S-3 directly (i.e., without

\(^1\)Of this $600,000, roughly $95,000 could also be saved by S-2 were it allowed to freely change initial enrichment for Reactors B and D.
any penalty) and with penalties of a half or one million dollars per change.

5.7.2 Sensitivity to Horizon Length

Ideally, a management planning tool should yield consistent results whether the planning horizon is taken to be four, five or six years into the future. To test this aspect of the model, the results in Figure 5.25 were produced using the Case I (see Table 5.8) detailed optimized solutions for Strategies 2 (see Figure 5.6) and 3 (see Figure 5.7). However, the operating revenue requirement summation [Equation (2.17)] for the 72 months covered by the horizon of Case I was only carried up to and including the horizon indicated on the abscissa (enrichment change penalties were not included). The disturbing oscillatory nature of the comparison is almost identically matched by the shifts in downtime advantages which are also presented. In a particular period, if an additional reactor is down for refueling in Strategy S-3, then S-3 will lose a reactor-month of downtime advantage. More importantly each nuclear MWH foregone must be made up with fossil replacement energy. Thus, each month of downtime means roughly 300 GWH (discounted) of short-term replacement energy at 4.0 $/MWH versus nuclear average costs of 2.0 $/MWH. The net result: each reactor-month of downtime five years in the future costs roughly $600,000.
Figure 5.25

Cost and Downtime Advantage of S-3 versus S-2 as Function of Horizon Length

---

UNPENALIZED COST ADVANTAGE OF S-3 RELATIVE TO S-2 (10^6 $)

DOWNTIME ADVANTAGE OF S-3 RELATIVE TO S-2 (REACTOR-MONTHS)

HORIZON LENGTH (MONTHS)
The next question is "What causes these shifts in downtime advantage?" The answer is given in Figure 5.26, a composite of the two month refueling outages in each strategy presented in Figures 5.5 to 5.7. [Note the regularity of S-1's annual refuelings and the fact that every refueling window involves at least two months of simultaneous or "stacked" refuelings. S-2 and S-3, by selectively skipping over a window with different reactors (see Section 5.3.3), are able to avoid simultaneous refuelings until the fifth year.] S-3's two reactor-month downtime advantage at 48 months can be pin-pointed as actually occurring during the first full window of the first year when S-3's immediate shift to longer cycles dictated immediately skipping a summer. Further note that although the four year horizon ends exactly after a refueling for both S-2 and S-3, S-2 shifts the next refueling back one month. This causes the temporary one reactor-month shift in downtime advantage just after four years.

At the six year horizon, shown on Figure 5.26, note both S-2 and S-3 conveniently terminate exactly after a refueling. Now consider the relative position of their simultaneous refueling with respect to a five year horizon. In S-3, it occurs before the five year cutoff, but in S-2, it is postponed until just before the summer. The window, as a whole, involves no shift in downtime advantages, but if the horizon occurs within the window (e.g., 5 year horizon) an anomalous one million dollar added advantage may
FOR EXAMPLE, TWO MONTH REFUELING OF UNIT B

FORBIDDEN SUMMER MONTHS (PARTITIONS)

REFUELING WINDOW

TIME (YEARS)
accrue to S-2. Since no refuelings occur during the summer and, in fact, the summers represent the partitions between the windows, it is recommended that a single horizon coinciding with one of these partitions be chosen. Note that if the horizon occurs in any of the six summer months appearing in Figure 5.25, S-3 is cheaper by roughly $700,000 (if no enrichment change penalty is applied).

In the absence of utility refueling constraints (e.g., no refuelings in summer) that create the computationally convenient windows and partitions, a single, long horizon could still be calculated in detail. However, prudence would dictate developing shorter horizon results such as those in Figure 5.25 to permit a more intelligent evaluation of strategy cost differences.

Though the above horizon-at-partition conclusion is presented with verification, a solid conclusion concerning which partition must await the second generation nuclear power management model possessing detailed CORSOM's. As an interim rule of thumb, intuition suggests that the horizon ought to include a complete core of freely specified enrichments for each reactor. In other words, the horizon should be far enough into the future to predict completely the discharge characteristics of the next reload enrichment to be finalized (i.e., actually ordered from vendor) for each reactor.

In summary, choice of a proper horizon is imperative, but not difficult. If the worst comes to the worst, a long
horizon evaluated per Figure 5.25 would always be valid and helpful. In any event, for planning horizons on the order of five or six years, differences in total system cost under a few hundred thousand dollars are best viewed as insignificant (see Section 5.8.5). Such dilemmas ought to be reconciled based on other criteria—e.g., the most flexible, the easiest to implement or the most reliable strategy.

5.7.3 Sensitivity to Present Value Rate

The optimized results for the three Cases with different present value rates are presented in Table 5.15 for Case III (0%), Table 5.16 for Case II (7%) and Table 5.17 for Case IV (12%).

By recognizing three general cost components of each strategy, much insight can be gained. They are (1) all fossil fuel related costs, (2) direct nuclear outlays and (3) carrying charges on the nuclear outlays. At a 7% present value rate, nuclear carrying charges are ~25% of nuclear outlays while fossil carrying charges are relatively insignificant.

As the present value rate increases, the revenue requirements for (1) and (2) decrease slowly while those for component (3) rise sharply. The result is that as the present value rate increases, the heavier a strategy's reliance on nuclear energy, the less advantageous that strategy becomes. The optimum choice may not change, but
<table>
<thead>
<tr>
<th>Strategy</th>
<th>S-1</th>
<th>S-2</th>
<th>S-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downtime to horizon (reactor-months)</td>
<td>38</td>
<td>33</td>
<td>31</td>
</tr>
<tr>
<td>Average cycle length (months)</td>
<td>12</td>
<td>14.5</td>
<td>15.2</td>
</tr>
<tr>
<td>System nuclear capacity factor</td>
<td>0.638</td>
<td>0.647</td>
<td>0.651</td>
</tr>
<tr>
<td><strong>10^6$ (10^6 MWH)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fossil fuel</td>
<td>212.434</td>
<td>203.326</td>
<td>199.928</td>
</tr>
<tr>
<td>Startup-shutdown cost</td>
<td>1.684</td>
<td>1.430</td>
<td>1.373</td>
</tr>
<tr>
<td>Emergency purchases</td>
<td>0.528</td>
<td>0.355</td>
<td>0.299</td>
</tr>
<tr>
<td>Nonnuclear production</td>
<td>214.646</td>
<td>205.111</td>
<td>201.600</td>
</tr>
<tr>
<td>Nuclear fuel</td>
<td>158.416</td>
<td>153.987</td>
<td>154.678</td>
</tr>
<tr>
<td>System production</td>
<td>373.062</td>
<td>359.098</td>
<td>356.278</td>
</tr>
<tr>
<td>Fixed firm purchase</td>
<td>108.624</td>
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<td>108.624</td>
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<tr>
<td>Penalty for short-notice enrichment changes</td>
<td></td>
<td></td>
<td>2.000</td>
</tr>
<tr>
<td>System Total</td>
<td>481.686</td>
<td>467.722</td>
<td>466.902</td>
</tr>
</tbody>
</table>

TABLE 5.15
REVENUE REQUIREMENTS AND UNDISCOUNTED ENERGY FOR CASE III
(48 Month Horizon, 0% P.V. Rate, Reference Nuclear Unit Costs, No Shape Constraints)
TABLE 5.16
REVENUE REQUIREMENTS AND UNDISCOUNTED ENERGY FOR CASE II
(48 Month Horizon, 7% P.V. Rate, Reference Nuclear Unit Costs,
No Shape Constraints)

<table>
<thead>
<tr>
<th>Strategy</th>
<th>S-1</th>
<th>S-2</th>
<th>S-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downtime to horizon (reactor-months)</td>
<td>38</td>
<td>33</td>
<td>31</td>
</tr>
<tr>
<td>Average cycle length (months)</td>
<td>12</td>
<td>14.5</td>
<td>15.2</td>
</tr>
<tr>
<td>System nuclear capacity factor</td>
<td>0.638</td>
<td>0.647</td>
<td>0.651</td>
</tr>
</tbody>
</table>

\[10^6\]$
(10^6 \text{ MWH})$

<table>
<thead>
<tr>
<th></th>
<th>S-1</th>
<th>S-2</th>
<th>S-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuel</td>
<td>184.223</td>
<td>176.348</td>
<td>173.250</td>
</tr>
<tr>
<td></td>
<td>(51.703)</td>
<td>(50.061)</td>
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the advantage will decrease. For example, comparing S-1 (the annual strategy) and S-2 (the gradual shift to longer cycles), S-2 is always favored but the savings decreases from 14.0 to 6.7 million dollars as the rate goes from 0 to 12 per cent.

To investigate such changes in more detail, Figure 5.27 presents a cost comparison of S-2 (gradual shift) and S-3 (immediate shift) for the three rates involved. S-3 uses more nuclear energy and less fossil. Therefore, it possesses a non-nuclear savings of 3.5 million dollars at 0 per cent. However, as a result of nuclear carrying charges, S-3's added nuclear cost increases six times as fast as the fossil advantage itself decreases! On an unpenalized basis, S-3 is the optimum at a 7% present value rate, but S-2 is optimum at 12 per cent. The break-even point is 9-1/4 per cent. Naturally, the higher the penalty, the more S-3 must have saved prior to applying the penalty. The result: one million dollars in penalties breaks even at 5-1/2% while two million requires 2-1/4%. With any reasonable penalty and present value rate, S-2 is clearly optimum over both S-1 and S-3.

An interesting question is now posed: Suppose a mythical fourth strategy differed from S-2 by only $500,000. What size error in forecasting the present value rate would completely mask this difference? Using the slope from Figure 5.27, an error of approximately 1-3/4% in the present
Figure 5.27
Non-Nuclear Savings and Nuclear Cost for S-3 versus S-2
as Function of Present Value Rate
value rate would shift the total cost advantage $500,000. Such a forecasting error is not altogether improbable. Thus, as standard practice, all near optimal policies should be evaluated and ranked at several additional present value rates (say, the nominal ± 2%), not at the nominal rate alone. In this manner, strategies extremely sensitive to the present value rate may be eliminated.

In the above recommendation, note the word "evaluated", not "re-optimized". All of the results quoted in this Section are for re-optimized solutions using the specified present value rate. Practically speaking, the computer expense of re-optimizing the Case II solutions was not necessary. Re-optimization saved less than $90,000 each on five out of the six cases involved [S-3 saved $275,000 if there was no time value of money (0%)].

5.7.4 Sensitivity to Nuclear Unit Costs

The optimized results for the cases involving Low, Reference, and High nuclear unit costs (see Table 5.7) are presented in Table 5.18 for Case V (Low), Table 5.19 for Case II (Reference) and Table 5.20 for Case VI (High). From a total cost standpoint, S-2 remained the optimum choice. The trends in the S-2 vs. S-3 comparison are portrayed in Figure 5.28.

Of course, variations in nuclear costs do not affect S-3's 3.2 million dollar fossil savings. But S-3's increased nuclear energy does result in increased separative


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<th>Strategy</th>
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<td>Downtime to horizon (reactor-months)</td>
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<td><strong>System Total</strong></td>
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TABLE 5.19
REVENUE REQUIREMENTS AND UNDISCOUNTED ENERGY FOR CASE II
(48 Month Horizon, 7% P.V. Rate, Reference Nuclear Unit Costs,
No Shape Constraints)

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<tr>
<th>Strategy</th>
<th>S-1</th>
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<tr>
<td>Fossil fuel</td>
<td>184.223</td>
<td>176.348</td>
<td>173.250</td>
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Non-Nuclear Savings and Nuclear Cost for S-3 versus S-2 as Function of Nuclear Unit Costs

- ADDITIONAL NON-NUCLEAR PRODUCTION SAVINGS FOR STRATEGY 3
- UNPENALIZED ADDITIONAL NUCLEAR FUEL COST FOR STRATEGY 3
- $2 MILLION IN PENALTIES
- $1 MILLION IN PENALTIES

NUCLEAR UNIT COST SET
LOW (75%)  REFERENCE (100%)  HIGH (125%)

COST OR SAVINGS (10^6 $)
work requirements. These, in turn, cause S-3 to suffer a larger disadvantage as unit costs increase. Unpenalized, S-3 is able to maintain at least a $300,000 advantage in the entire range investigated. However, even one million dollars in penalties turns the choice around for the same range.

As for the forecasting error that results in $500,000 closer competition, a 40% change in Reference nuclear unit costs is required. This would appear to border on the improbable. However, the characteristics of the six PWR reactors comprising the hypothetical utility are so similar, that generalizations to all types of nuclear reactors are impossible. A utility possessing a broad mix of reactor types (PWR, BWR, HTGR, LMFBR, GCFR, etc.) and sizes would very likely find that small shifts within various unit cost components would alter the reactor loading order. For instance, rising plutonium value decreases LWR fuel costs as a credit, but increases LMFBR fuel costs. Such an investigation is clearly beyond the scope of the current nuclear power management model because of QKCORE's inherent limitations (see Section 5.2). In the future, this may well be the most interesting investigation of all.

A word about re-optimizing the Case II solutions is again in order. With the qualifications just mentioned regarding other reactor types, re-optimization, though performed, was not necessary. Since the reactors were nearly
identical, energy was not re-optimized significantly. The nuclear cost was merely re-evaluated. The average cost savings for each of the six perturbed solutions was less than $15,000.

5.7.5 Sensitivity to Non-Nuclear Costs

To evaluate the non-nuclear cost components, the results of Case II in Table 5.14 are used. Since the non-nuclear cost components only affect SYSINT results directly, parameterization of these costs did not require further SYSOPT runs.

Cursory examination of Table 5.15 indicates immediately that startup-shutdown cost and emergency power purchases do not vary by more than $300,000 from strategy to strategy. On the other hand, fossil fuel cost can vary by 10 million dollars or more. On account of their relative size and absolute size with respect to various forecasting and core modeling errors, the comparison is more convenient if all non-nuclear components are lumped together. The obvious parameter is \( \phi_F \) cents per MegaBTU for fossil fuel. If this were to increase, startup-shutdown costs would increase proportionally since the major cost component is incurred due to sensible heat requirements during startup (see Figure 2.6). Emergency power purchases should also be proportional to fossil fuel cost if the neighbor supplying the energy relies on fossil fueled equipment to generate it.
With these assumptions, Figure 5.29 is presented indicating breakeven points for S-2 (gradual shift) versus S-3 (immediate shift) as a function of fossil fuel cost. The higher the cost of fossil fuel, the larger the fossil savings of S-3 and the larger penalty it can successfully absorb. Unpenalized, S-3 breaks even at 33¢/MegaBTU. Each one million dollars in penalties requires another 12-1/2¢/MegaBTU. Thus, with any reasonable penalty, S-2 is again the optimum.

More importantly, note the forecasting error required to equalize a $500,000 difference—merely 6-1/4¢/MegaBTU. Given the realities of today's fossil fuel marketplace and the environmental concern, forecasting fossil fuel costs five or six years into the future within 6¢/MegaBTU is a near impossible task. This forecast very likely could turn out to be the critical item in the overall model input.

The models of interfuel competition currently under development in many institutions [e.g., (11)] may aid in pinpointing, or at least bracketing more closely, the future trends in fossil fuel costs.

In short, fossil fuel thermal energy cost appears to be one of the critical input data.

5.8 Critical Questions Revisited

Section 5.1 posed six critical questions pertinent to the development of any management planning tool. The following sections provide a summary of their answers as they apply
Figure 5.29

Non-Nuclear Savings and Nuclear Cost for S-3 versus S-2 as Function of Fossil Fuel Cost

- ADDITIONAL NON-NUCLEAR PRODUCTION SAVINGS FOR STRATEGY 3
- $2 MILLION PENALTIES
- $1 MILLION PENALTIES
- UNPENALIZED ADDITIONAL NUCLEAR FUEL COST FOR STRATEGY 3
- LOWER LIMIT BEFORE VIOLATING ASSUMPTION THAT ALL NUCLEAR ENERGY IS CHEAPER ANY FOSSIL ENERGY

FOSSIL FUEL COST ($/MEGABTU) vs. COST OR SAVINGS ($10^6$)
to the current nuclear power management multi-year model and, in particular, to the SIM and SOM developed in this work.

5.8.1 To What Problems is the Model Applicable?

The complete model of Figure 2.21 applies to the multi-year management of utility systems possessing any types and amounts of fossil, nuclear, hydro and pumped-hydro equipment. As implemented in the SYSINT and SYSOPT computer models of the SIM and SOM, respectively, only fossil and nuclear equipment are currently permitted. Addition of the other two types should receive a high priority. A computerized RAMM should be interfaced with the models to permit the investigation of many strategies. Development of detailed CORSOM's for each reactor type are required to replace the limited test simulator QKCORE.

Once these improvements have been made, the scope of the problems the model could analyze are almost numberless. Input to the model consists of forecasts, operating constraints, initial conditions, unit costs, etc. The optimized outputs include period production schedules, fossil maintenance-nuclear refueling schedules and nuclear reload parameters. The combination and permutations of altered inputs affecting outputs generates an enormous number of possibilities.
5.8.2 What Assumptions are Required?

Though the current computerized version of the nuclear power management model contains several simplifying assumptions, only one of the assumptions is actually inherent in the model of Figure 2.21. The others, enumerated below, could be relaxed by reprogramming the affected portions.

The pivotal assumption involves the permanent relationship between nuclear and fossil fuel costs. Namely, nuclear incremental costs are sufficiently less than even the best fossil incremental costs, that for the foreseeable future, nuclear energy will be utilized so as to displace as much fossil energy as possible. This maximization of nuclear energy dictates the SIM's loading order segregation into must-run fossil minimums, nuclears and remaining fossils (see Section 3.2) regardless of intra-nuclear cost differences. The SOM then minimizes the cost of producing this nuclear energy.

The SOM's inner iterative procedure involves passing cycle energy vectors to the CORSOM's and receiving cost information as a feedback loop to test for convergence and determine the cycle energy vectors for the next iteration. If the key assumption were to be relaxed or should it become invalid due to unforeseen price shifts, the termination of the feedback loop would have to be shifted to the SIM.² For then, changes in nuclear incremental costs would

²The ORSIM model, currently under development at Oak Ridge National Laboratory (14), is of this more general type.
also alter the fossil-nuclear competition (i.e., loading order), resulting in varying amounts of fossil energy and fossil cost at each iteration. The objective function in the SOM would become the total system cost directly, not merely the nuclear cost as at present.

Though the nuclear-vs.-fossil cost assumption does restrict the model's generality, the prospects of violating it are low and the computational savings may be significant.

The following additional assumptions were made in order to simplify programming the models:

(1) At time zero, none of the nuclear cores is so depleted as to represent a scarce resource. When further development enables the SIM to handle scarce resource hydro units, this assumption may be relaxed by treating energy-short nuclear plants similarly.

(2) All forecasts (even six years into the future) are 100% accurate (i.e., a deterministic future). As recommended in Section 5.3.1, much work needs to be done in this area with regard to confidence limits on the various results.

(3) For such a non-expansion planning model, only operating costs need be included in the objective function since capital costs and related carrying charges are already fixed by the additions and
retirements specified and held constant for all strategies (see Section 2.1.3). The addition of these and other cost components to the model would complete a useful tool for multi-year or longer planning.

(4) The incremental heat rate of each nuclear plant was assumed constant by the SOM over the operating range of interest. As Section 2.4.2 pointed out, proprietary data on today's PWR's and BWR's confirm the assumption. Future plant types, as well as newer generations of the above, may force re-evaluation of this assumption.

(5) The utility system contains enough must-run fossil equipment to provide sufficient spinning reserves to permit all nuclear upper increment capacity (group 3 in Figure 3.8) to be scheduled as a single, continuous block of capacity. In other words, spinning reserve requirements do not make it necessary to mix groups 3 and 4 (remaining fossil capacity). This condition appears likely to prevail for many years, i.e., as long as the system contains large fossil units that cannot be shut-down and then started up readily and reliably.

(6) All incremental cost curves are continuous and monotonically increasing. All data produced by the simple QKCORE model bore out this assumption.
Such behavior assures convexity of the SOM's operating cost objective function and permits the use of a standard NP optimization package.

(7) Finally, all nuclear minimums are base-loaded. One implied result is that there are no nuclear startup-shutdowns. In addition, this assumption coupled with assumption (4) allows the analytical simplifications that lead to Equation (2.52) relating thermal and electrical energy directly. This same simplification facilitates the interfacing of the SIM and SOM, but, as with the other six simplifications, it could be relaxed.

As for recommendations concerning further development, numbers (1) and (2) ought to have high priority; (3) through (5), medium priority; (6) and (7), low priority.

5.8.3 Does the Method Converge to an Optimum?

As the discussion in Section 5.6.1 pointed out, the inner iteration on system cost did converge. Considering the other errors inherent in the models (see Section 5.8.5), convergence can be called complete. Convergence was, however, slow. This prompted the recommendation to study the problem further.

Convergence of the outer shape iterations (see Section 5.6.2) was obtained with only slight increases in predicted system total cost. However, outer convergence was also slow.
Increasing the amount of piecewise-linearization would aid both the inner and outer convergence rates.

5.8.4 Is it the Global Optimum?

Globality hinges on two key issues:

(1) Was the globally optimal strategy even included as a possible alternative?

(2) Did the SOM achieve the minimum system cost for each and every strategy that was evaluated?

The answer to the first question depends on the completeness of the RAMM. As for the second question, assumption (5) of Section 5.8.2, relative to the incremental cost curves, guaranteed convexity of the objective function (see Section 4.4.2). And this, in turn, guaranteed the minimization of each strategy subject only to a posterior feasibility check.

Barring decreasing incremental cost curves, globality thus depends solely on providing a suitable RAMM.

5.8.5 How Accurate are the Results?

The forecast error analysis of Sections 5.7.3 to 5.7.5, combined with the work of Watt (55), indicate that strategy versus strategy total cost differences are probably accurate only to within a minimum of $500,000 when compared with the actual (versus calculated) total costs realized over five or six years (on the order of $500,000,000). The major contributions to this error are CORSOM inaccuracies (> $100,000 per reactor) and poor forecasts regarding fossil fuel costs,
present value rate, customer load demands and unit availabilities. The latter two forecasting errors have been totally ignored in this initial modeling work and should, therefore, be high on the list for future development effort.

5.8.6 What are the Computational Requirements?

Computational requirements have been previously discussed in Sections 3.6, 4.6 and 5.6.4.
CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

This work has presented a nuclear power management multi-year model suitable for 5 to 10 year multi-reactor fuel management studies. The overall model consists of four sub-models:

(1) Refueling and Maintenance Model (RAMM),
(2) System Integration Model (SIM),
(3) System Optimization Model (SOM), and
(4) CORe, Simulation and Optimization Model (CORSOM) for each reactor type.

The SIM and SOM sub-models have been developed in this study and are discussed in detail. Computerized versions of these (SYSINT and SYSOPT, respectively), were programmed and tested. Numerical results were presented not only to evaluate the models, but also as examples of the overall model's versatility. As an aid in further model development, the following sections summarize the main conclusions and recommendations. (All computation times given below are in terms of an IBM 370 model 155 computer.)

6.2 Conclusions

(1) While fossil unit instantaneous power levels are chosen so as to maintain equal fossil incremental costs, the nuclear unit period energy production schedules should be
chosen so that all reactors are operating at the same nuclear incremental cost.

(2) The overlapping of irradiation cycles for the various reactors plus Conclusion (1) above leads to idealized production schedules yielding a constant nuclear incremental cost regardless of time. However, such production schedules may not be feasible. The computer code SYSOPT determines the optimum feasible production schedule that approaches this ideal as closely as possible (i.e., with minimum total system revenue requirement).

(3) While nuclear average fuel costs are on the order of 1.8 to 2.2 $/MWH, the incremental system cost of designing more nuclear energy into a given cycle is on the order of 0.8 to 1.6 $/MWH. During nightly low load periods, it would be economical to sell power to neighboring utilities in this lower price range. In fact, it is even more advantageous to use excess nuclear capacity for pumping at a stored-hydro station.

(4) Even with fossil fuel costing as little as 25¢/Mega-BTU (and rising), the best-plant fossil incremental cost is at least 2.0 $/MWH. Considering that even the highest nuclear incremental fuel costs today are less than 1.6 $/MWH, the conclusion is that nuclear incremental costs will be less than fossil incremental costs for the foreseeable future.

(5) As a result of Conclusion (4) above, nuclear power should always be operated so as to displace maximum fossil energy.
(6) Another conclusion based on Conclusion (4) above is that an economic incentive exists for lengthening nuclear irradiation cycles in terms of both energy and time. Increasing nuclear incremental costs are more than justified by the reduction in average annual fossil replacement energy required during refueling downtime. In addition, minimum total system nuclear downtime (subject to burnup constraints) appears to be a good a priori measure of the ranking of various refueling and maintenance strategies.

(7) One of the key input parameters was shown to be the fossil thermal energy cost. A small forecasting error in this number alone (roughly 6 out of 40 $/MegaBTU) altered example four year strategy cost differences by $500,000 (out of a total difference of $1,500,000).

(8) Using the latest in a PWR in-core model (41) and assuming convergence in five iterations, computation costs are on the order of 300 to 500 $ per strategy for a utility system possessing five nuclear reactors. Assuming a 1% annual savings in nuclear fuel revenue requirements alone, roughly $500,000 per year would be saved. Thus, scores of strategies could be run each year in order to up-date the current operating strategy, specify the next set of reload enrichments or, more importantly, re-optimize the strategy to account for large perturbations from the intended production or refueling and maintenance schedule. For example, how does the AEC's 1973 step price increase in enrichment charges from $32 to $38.50 per kg SWU (1) affect the
current operating strategy. The nuclear power management model's ability to quantify the complex utility system trade-offs (not only nuclear-vs-nuclear, but also, nuclear-vs-fossil) make it an indispensable planning tool for nuclear utility decision-makers.

(9) The reactor-by-reactor nuclear energy allocation problem may be cast as a network supply problem, permitting the use of network programming rather than the more general (and computationally difficult) linear programming.

(10) In addition, the Out of Kilter Network Program (45) was demonstrated to be sufficiently flexible to permit piecewise-linearization of the nuclear system optimization to an extent approaching quadratic programming in accuracy and exceeding it in the size of the problem solved.

(11) Several instances were encountered where strategy reoptimization was not necessary in order to evaluate the effect of various input data changes on previously optimized solutions. The capability to merely re-evaluate several previously optimized solutions eliminates the need for more than a single iteration per strategy and thus, reduces computational costs further.

(12) On a multi-year basis (~5 to 7 years), strategy-vs-strategy cost differences are estimated to be accurate only to within $200,000 per 1000 MW reactor (out of roughly $50,000,000) given perfect (i.e., deterministic) load and unit reliability forecasts. Estimates of the additional
cost inaccuracies incurred due to errors in these forecasts form part of the Recommendations.

(13) The multi-year planning horizon ought to include a full core of freely specified enrichments for each reactor. In other words, the horizon should be far enough into the future to completely predict the discharge characteristics of the next reload enrichment to be finalized (i.e., actually ordered from a vendor) for each reactor. In addition, it is convenient to place the planning horizon in a forbidden maintenance period in order to minimize distortion of strategy-vs-strategy cost differences due to horizon end effects. Beyond the planning horizon, cycle energies should be postulated so as to maintain the individual operating philosophy ("character") of each strategy, not return to an arbitrary final state.

6.3 Recommendations

(1) The Booth-Baleriaux probabilistic utility model within SYSINT represents the latest in utility system simulation. The current model is capable of simulating a 100 unit utility system (with up to 5 valve points per unit) for up to 100 time periods. Since nuclear, fossil and peaking equipment are currently included, the addition of hydro and pumped-hydro equipment (i.e., types involving scarce resource utilization) is highly recommended in order to complete the range of possibilities.
(2) The Booth-Baleriaux model's accuracy has been established by others (19, 36, 49) based on the reproduction of historical data. However, little if any testing has been done of the model's ability to project future production given forecasted loads and unit reliability data. Research into this area is needed to establish the sensitivity of the various results to unavoidable forecasting errors. Ultimately, the nuclear power management model should yield not only a numerical answer, but also a confidence interval around it.

(3) As a further refinement of the Booth-Baleriaux model, the two-state forced-outage model ought to be replaced with a more general model permitting unit derating (See Appendix A).

(4) The principal recommendation for SYSOPT model improvement is expansion of the network structure to permit decreased cycle energy step size (i.e., increased total cost linearization) and, hence, provide a closer approximation to quadratic programming (QP). (Due to problem size, the direct inclusion of a general QP model is out of the question.) Each iteration of SYSOPT (itself using less than 10 seconds for a six reactor utility system) requires another 20 minutes of computer time within even advanced in-core models (41). The reduction in step size is aimed at decreasing the number of iterations required to reach an acceptable optimum nuclear production schedule (hopefully, to as few as three of four).
(5) Other suggested improvements to SYSOPT include the capability to optimize nuclear units with varying incremental heat rates and to handle core reactivity stretch-out (i.e., allowance for reduced plant capacity). The inclusion of capital and other nonoperating revenue requirements in the total cost would complete a useful tool for multi-year (or longer) planning horizons.

(6) Relative to completion of the overall nuclear power management model put forth in this work, acceptable RAMM's already exist. The most severe deficiency is not due to either the SIM (SYSINT) or SOM (SYSOPT), but to a lack of computationally efficient CORSOM's for each reactor type. These in-core models represent the critical submodels requiring the greatest development effort. The PWR in-core model recently developed by Kearney (41), though a great leap forward in nuclear in-core simulation and optimization, still requires over 3 minutes per reactor per SYSOPT iteration. CORSOM's an order of magnitude faster are desired so that computation costs can be rendered truly insignificant compared with system savings.
A.1 Forced-Outage Models

Presented in this Appendix are derivations of the most general forms of the Booth-Baleriaux deconvolve-load-con- volve Equations (3.55), (3.56) and (3.57) of the multiple increment algorithm of Section 3.3.2.2. Whereas, Chapter 3 dealt exclusively with the two-state forced-outage model, this Appendix extends the model to permit derating of a unit. That is, a unit may be unable to produce at full capacity, yet be capable of operating at 90% of capacity—a 10% derating.

To distinguish the more general unit performance models from the simpler two-state model requires introducing their probability density functions (26) $f_G$ as a function of $P_G$, the generating unit output power capability. Thus, $f_G(P_G)dP_G$ represents the probability that, at a random instant of time, the unit's capability is limited to a range of $dP_G$ about $P_G$. For the two-state model (See Figure A.1), $f_G$ is one impulse ($q_r$) at $P_G=0$ and another ($p_r$) at $P_G=K_r$ since the unit is assumed not operable at all ($P_G=0$) or operable over the entire range to rated power ($P_G=K_r$).

The probability density functions $f_G$ for the general unit performance models are also shown in Figure A.1. With probability $p_r$, unit $r$ is capable of full power operation at
Figure A.1

Probability Density Functions of Unit Capability

- GENERAL DERATING MODEL

- DISCRETE DERATING MODEL

- TWO-STATE MODEL

$P_G$, GENERATOR OUTPUT CAPABILITY
\[ P_G = K_r (\equiv K_{ri}) \text{MW.} \] Conversely, with probability \( q_r \) the unit is not capable of producing any power at all \((P_G=0)\). For the "general derating" model, any fraction of capacity may be derated and, hence, \( f_G \) may have any shape between \( 0 < P_G < K_r \) so long as the standard probability density function requirement is met,

\[ \int_{-\infty}^{+\infty} f_G(P_G) dP_G = 1 \quad (A.1) \]

More specifically,

\[ P_r + q_r + \int_{0^+}^{K_r} f_G(P_G) dP_G = 1 \quad (A.2) \]

In the second "discrete derating" model, only whole increments of capacity may be derated and \( f_G \) is restricted to a probability mass function with each \( q_{ri} \) coinciding with the \( K_{ri} \) capacity increments. For \( i = 0 \), \( q_{ri} = q_r = q_r \) and

\[ P_r + \sum_{i=0}^{I-1} q_{ri} = 1 \quad (A.3) \]

Finally, for the special case \( q_{ri} = 0 \) for all \( i > 0 \), the discrete derating model reduces to the original (all-or-nothing) "two-state" model of Chapter 3,

\[ P_r + q_r = 1 \quad (A.4) \]
The symbol $\Phi$ is used to denote the complementary cumulative distribution function for $f_G$,

$$
\Phi(P_G) = 1 - \int_{-\infty}^{P_G} f_G(P) dP
$$

(A.5)

Thus, $\Phi(P_G)$ represents the probability that the unit is capable of generating $P_G$ or more at any random instant of time. Figure A.2 presents typical $\Phi$ for the three models.

When performing each convolution or deconvolution, the pertinent portion of the $K_{TMW}$ unit may be temporarily treated as a smaller "sub-unit" of $K_{TMW}$. Derived in this manner, the following equations are the most general.

For this smaller unit, $\Phi(P_G)$, by definition, falls to zero just beyond $K_{TMW}$. In addition, $f_G$ for the sub-unit is most easily viewed as the probability masses and derivative of this truncated $\Phi(P_G)$,

$$
f_G(P_G) = - \frac{d \Phi(P_G)}{dP_G}
$$

(A.7)

\footnote{Note that in this work, the complementary cumulative distribution function is defined to include the equality at the upper limit of the integral, in contrast to the usual placement of the equality with the cumulative distribution function itself,

$$
\Phi(P_G) = \frac{\text{Prob.(P<P_G)}}{\text{usual C.D.F.}} + \frac{\text{Prob.(P=P_G)}}{\text{usual C.C.D.F.}} + \frac{\text{Prob.(P>P_G)}}{1} = 1
$$

(A.6)

The distinction is purely academic as applied in this work.
Performance Probability Functions of Unit Capability

**General Derating Model**

**Discrete Derating Model**

**Two-State Model**
Of more immediate use than $f_G$ in determining equivalent load distribution is the forced-outage distribution $f_O(P_O)$ since only the unit's forced-outages contribute to the equivalent load [See Equation (3.5)]. To derive $f_O(P_O)$, use is made of the fundamental applied probability equation for changing random variables in a density function,

$$f_O(P_O)dP_O = f_G(P_G)dP_G$$

(A.8)

or

$$f_O(P_O) = f_G(P_G) \left| \frac{dP_G}{dP_O} \right|$$

(A.9)

Since,

$$P_G + P_O = K_{ri} + P_{Oi}$$

for the discrete case

(A.10)

$$\left| \frac{dP_G}{dP_O} \right| = 1$$

(A.11)

Hence,

$$f_O(P_O) = f_G(K_{ri} - P_O)$$

(A.12)

and $f_G$ is merely reversed (i.e., rotated about $0.5* K_{ri}$). Figure A.3 presents typical $f_O(P_O)$ for the three models.
Figure A.3

Probability Density Functions of Unit Capacity on Outage

GENERAL DERATING MODEL

DISCRETE DERATING MODEL

TWO - STATE MODEL
A.2 **Convolution**

As in Chapter 3, convolution is presented first since deconvolution is most easily expressed as the reverse of convolution. The aim of the convolution is to calculate an $F_w^r$ which includes (i.e., superscript $w = \text{with}$) unit $r$'s forced-outages (up to $K_{MW}$). The starting point is (1) the current equivalent load curve $F_{wo}^r$ that does not include any allowance for the outages of unit $r$ (i.e., $wo = \text{without}$) and (2) the sub-unit's own forced-outage distribution $f_0(P_0)$. (Since all references to $F$ are for the same unit increment $r$, the notation is shortened to $F_w$ and $F_{wo}$).

From the equivalent load definition Equation (3.5), the notation becomes

$$P_e = P_D + (P_0^') + (P_0^') \text{ Other Units}$$

$$\downarrow \quad \text{Unit } r$$

$$P_e^w = P_e^{wo} + P_0$$  \hspace{1cm} (A.14)

The equivalent load curve $F_{wo}$ is the complementary cumulative density function of $f_{wo}$ or the probability that $P_e \geq P_e^{wo}$,

$$F_{wo}(P_e) = 1 - \int_{-\infty}^{P_e^{wo}} f_{wo}(P) \, dP$$  \hspace{1cm} (A.15)
Convolution is performed in the manner of Drake (26) using Figure A.4. Thus, $F^w(P_e^w)$ represents the complementary cumulative distribution function of $f_{e,0}^w$ (i.e., below and to the left of the $P_e^w = \text{constant line}$),

$$F^w(P_e^w) = 1 - \int_{-\infty}^{+\infty} \int_{-\infty}^{P_e^w - P_W^w} f_e^w(P_e^w, P_O^w) \, dP_e^w \, dP_O^w$$  \hspace{1cm} (A.16)

Assuming the usual statistical independence between equivalent load ($f_{e,0}^w$) and un-included unit forced-outages ($f_0$),

$$f_{e,0}^w(P_e^w, P_O) = f_{e,0}^w(P_e^w) \cdot f_0(P_O) \hspace{1cm} (A.17)$$

Hence,

$$F^w(P_e^w) = 1 - \int_{-\infty}^{+\infty} \int_{-\infty}^{P_e^w - P_W^w} f_e^w(P_e^w) \cdot f_0(P_O) \, dP_e^w \, dP_O^w$$  \hspace{1cm} (A.18)

Since

$$1 = \int_{-\infty}^{+\infty} f_0(P_O) \, dP_O$$  \hspace{1cm} (A.19)
Figure A.4

Event Space Interpretation of Convolution

NOTE:

PLOTTED IN THE THIRD DIMENSION IS $f_{w0}^{\omega}(p_e, p_0)$ THE JOINT PROBABILITY DISTRIBUTION FOR SIMULTANEOUS $p_e^{\omega0}$ AND $p_0$.

ALL EVENTS SUCH THAT

$(p \geq p_e^w)$

ALL EVENTS SUCH THAT

$(p < p_e^w)$

$P_e^w = p_e^{\omega0} + p_0$

$P_0$, MAGNITUDE OF UNIT r'S DERATING

$P_e^{\omega0}$, EQUIVALENT LOAD WITHOUT ALLOWANCE FOR UNIT r'S DERATING
Equation (A.18) can be factored into

\[
F_W(P_e) = \int_{-\infty}^{+\infty} f_0(P_0) \left[ 1 - \int_{-\infty}^{P_e-P_0} f_W(P_e) dP_e \right] dP_0
\]

(A.20)

Since the bracketed term is, by definition Equation (A.15),
the complementary cumulative distribution function of
\( f_{WO} \), i.e., \( F_{WO}(P_e-P_0) \), then

\[
F_W(P_e) = \int_{-\infty}^{+\infty} f_0(P_0) F_{WO}(P_e-P_0) dP_0
\]

(A.21)

Reducing the \( P_e \) notation to merely \( P_e \), the result is the
convolution of the general derating model,

\[
F_W(P_e) = \int_{-\infty}^{+\infty} f_0(P_0) \cdot F_{WO}(P_e-P_0) dP_0
\]

(A.22)

For the discrete derating model of Equation (A.3),
this reduces to

\[
F_W(P_e) = P_r F_{WO}(P_e) + \sum_{i=0}^{L-1} q_{ri} F_{WO}(P_e-K_{ri}-K_{ri})
\]

(A.23)

Finally, the two-state model of Equation (A.4) yields the
original Equation (3.57),

\[
F_W(P_e) = P_r F_{WO}(P_e) + q_r F_{WO}(P_e-K_{ri})
\]

(A.24)
A.3 Deconvolution

Deconvolution seeks to regain $F^{WO}$ given $F^W$. That is, it strips out the forced-outages of the $K_{r, MW}$ unit.

Performing the integration of Equation (A.22) from $-\infty$ to $0^+$ (See Figure A.1),

\[ F^W(P_e) = p_r F^{WO}(P_e) + \int_{0^+}^{\infty} f_0(P_0) F^{WO}(P_e - P_0) dP_0 \]  
\[ (A.25) \]

Solving for $F^{WO}(P_e)$, deconvolution for the general derating model becomes

\[ F^{WO}(P_e) = \frac{1}{p_r} \left[ F^W(P_e) - \int_{0^+}^{\infty} f_0(P_0) F^{WO}(P_e - P_0) dP_0 \right] \]  
\[ (A.26) \]

For the discrete derating model, Equation (A.23) rearranges into

\[ F^{WO}(P_e) = \frac{1}{p_r} \left[ F^W(P_e) - \sum_{i=0}^{\infty} q_{ri} F^{WO}(P_e - K_{r, ri} + K_{r, ri}) \right] \]  
\[ (A.27) \]

Likewise, the two-state model of Equation (3.55) may be obtained from Equation (A.24),

\[ F^{WO}(P_e) = \frac{1}{p_r} \left[ F^W(P_e) - q_r F^{WO}(P_e - K_{r, r}) \right] \]  
\[ (A.28) \]
A.4 Loading

In performing the expected loading calculation of Figure A.5, the statistical independence is again invoked,

\[ \begin{bmatrix} \text{Energy increment} \\ \text{Prob. at } P_e = P_{ri} + \delta K \\ \text{is generated} \end{bmatrix} = \text{Prob. at } P_e \text{ demanded} \times \text{Prob.} \begin{bmatrix} \delta K \text{ increment of capacity is operable, i.e.,} \\ P_G > K_{r,i-1} + \delta K \end{bmatrix} \]

\[ = F^{WO}(P_{ri} + \delta K) \cdot \mathcal{P}(K_{r,i-1} + \delta K) \]  

(A.29)

Integrating from \( \delta K = 0 \) to \( \delta K = \Delta K_{ri} \) and multiplying by \( T' \), the length of the time period, the general derating model is loaded according to

\[ E_{ri} = T' \int_{P_{ri}}^{P_{ri} + \Delta K_{ri}} F^{WO}(P_e) \mathcal{P}(K_{r,i-1} + P_e - P_{ri}) dP_e \]  

(A.31)

For the discrete derating model (See Figure A.2),

\[ \mathcal{P}(K_{r,i-1} + \delta K) \equiv \mathcal{P}_{ri} = \text{constant for } 0 \leq \delta K \leq \Delta K_{ri} \]

(A.32)
Figure A.5

Load Demanded of $\Delta K_{ri}$, Unit Increment

$P_e$, EQUIVALENT LOAD

$P_e^o$, PROB. ($P_e \geq P_e^o$)
and, hence,

\[ E_{ri} = T' P_{ri} \int_{P_{ri}}^{P_{ri} + \Delta K_{ri}} F^{WO}(P_e) dP_e \]  \hspace{1cm} (A.33)

The two-state model \((P_{ri} = P_r)\) reduces to Equation (3.56),

\[ E_{ri} = T' P_r \int_{P_{ri}}^{P_{ri} + \Delta K_{ri}} F^{WO}(P_e) dP_e \]  \hspace{1cm} (A.34)

A.5 Summary

Table A.1 presents a summary of the deconvolve-load-convolve sequence of calculations for each forced-outage models.
Table A.1

Summary of Booth-Baleriaux Equations for Various Forced-Outage Models

<table>
<thead>
<tr>
<th>General Derating Model</th>
<th>Discrete Derating Model</th>
<th>Two-State Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>(F^{\omega}(P)) = (\frac{1}{Pr}\left[F^{\omega}(P) - \sum_{i=0}^{\omega-1} q_{ri} F^{\omega}(P - K_{rd} + K_{ri})\right])</td>
<td>(E_{ri} = T'^{\prime} \int_{P_{ri}}^{P_{ri} + \Delta K_{ri}} F^{\omega}(P) \sigma(P_e - P_{ri} + K_{ri}) dP_e)</td>
<td>(F^{\omega}(P) = p_r F^{\omega}(P) + q_r F^{\omega}(P - K_{rd}))</td>
</tr>
<tr>
<td>(F^{\omega}(P) = \int_{-\infty}^{+\infty} F^{\omega}(P) F^{\omega}(P - P_0) dP_0)</td>
<td>(F^{\omega}(P) = \frac{1}{Pr}\left[F^{\omega}(P) - \frac{1}{\omega+1} q_{ri} F^{\omega}(P - K_{rd} + K_{ri})\right])</td>
<td>(F^{\omega}(P) = p_r F^{\omega}(P) + q_r F^{\omega}(P - K_{rd}))</td>
</tr>
<tr>
<td>(E_{ri} = T'^{\prime} \int_{P_{ri}}^{P_{ri} + \Delta K_{ri}} F^{\omega}(P) dP_e)</td>
<td>(F^{\omega}(P) = \frac{1}{Pr}\left[F^{\omega}(P) - \sum_{i=0}^{\omega-1} q_{ri} F^{\omega}(P - K_{rd} + K_{ri})\right])</td>
<td>(E_{ri} = T'^{\prime} \int_{P_{ri}}^{P_{ri} + \Delta K_{ri}} F^{\omega}(P) dP_e)</td>
</tr>
</tbody>
</table>

Notes:
1. \(D = \text{DECONVOLVE}, \ L = \text{LOAD}, \ C = \text{CONVOLVE}\)
2. Identity of sub-unit \(K_{rd}\) changes between deconvolution and convolution steps since \(\text{DECONVOLVE} \neq \text{CONVOLVE}\) to account for \(\Delta K_{rd}\) on just loaded.
3. In accordance with Equation (A.7) and note (2), \(p_r\) for sub-unit \(K_{rd}\) is actually original \(G(P_0)\) (for entire unit \(K_r\)) evaluated at \(P_0 = K_{rd}\).
Section 4.2.4 explained the need for a shape constraint in the SOM and derived an approximate variance method for establishing the feasibility of postulated $F_r$ shapes. This Appendix presents the rigorous (i.e., necessary and sufficient) but cumbersome, area method. Recall that given an $F_e$ system shape (cf. Figure 4.9 and Figure B.1) over the system nuclear upper increment capacity from 0 to $k'_T$, the problem is to determine if a set of postulated period energies $E_r$ (that resulted in the $F_r$ postulated average reactor shape) could be satisfied by a feasible detailed loading order.

The area method is based on an observation relative to the mapping process of Figure 4.7. That is, over the range from 0 to any equivalent load $P$, it is impossible to reorder $F_e(P_e)$ into a detailed $F_r(P_r)$ such that the resulting $F_r(P_r)$ contains more energy than the original $F_e(P_e)$. In other words, there can be no pre-production of equivalent load energy. Thus,

$$\int_0^P F_r dP_r \leq \int_0^P F_e(P_e) dP_e \quad (B.1)$$

or
Figure B.1

Area Method for Determining Feasibility
(cf. Figure 4.9)

NET EFFECT OF CONSTRAINT EQ. (B.2)

\[ A_1 + A_2 \geq B_1 + B_2 \]
\[ A_1 + A_2 + A_3 \geq B_1 + B_2 + B_3 \]

Eq. (4.39) GUARANTEES THAT
\[ A_1 + A_2 + A_3 + A_4 = B_1 + B_2 + B_3 + B_4 \]

F, PROBABILITY \( (P_e \geq) \)

\( F_e \) SYSTEM SHAPE

\( \bar{F}_r \) POSTULATED AVERAGE REACTOR SHAPE

ON NUCLEAR UPPER INCREMENTS
Hence, the net area between $F_e(P_e)$ and $\overline{F}_r(P_r)$ from 0 to any $P$ must be positive (See Figure B.1).

If the inequality of Equation (B.1) or (B.2) does not hold at any single $P$, the required detailed loading order does not exist (e.g., see Figure 4.6). Herein, lies the difficulty with the area method: it must be checked at every $P$ or at least at several well-chosen ones. Though the method is rigorous, the amount of computer data handling and storage are unwieldy even using a linear approximation to $F_e$. 

\[ 0 \leq \int_0^P (F_e(P_e) - \overline{F}_r) dP_e \quad (B.2) \]
Section 2.1.2.3 presented the Five-Unit Reference Utility System. Unit characteristics were detailed in Figure 2.2. Table C.1 summarizes the data for each valve point. Figure C.1 repeats the $F_D$ customer load-duration curve of Figure 2.9 for the 730 hour month.

Table C.2 presents a SYSINT Fortran-to-text symbol cross-reference table. The following Tables C.3 to C.20 present the numerical data of SYSINT's Booth-Baleriaux model for each of the six Examples, in turn. (Section E.3 presents the computer input decks actually used in executing the Examples.)
Table C.1

Unit Characteristics for Reference Utility System

Total Capacity - 2000 MW

<table>
<thead>
<tr>
<th>Unit Name</th>
<th>Type</th>
<th>Rated Cap. $K_r$ (MW)</th>
<th>Perf. Prob. $P_r$ (%)</th>
<th>SUSD. Cost $</th>
<th>$K_{rl}$ (MW)</th>
<th>$r_{rl}$ ($/MWH)</th>
<th>$K_{r2}$ (MW)</th>
<th>$r_{r2}$ ($/MWH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Peaking</td>
<td>100</td>
<td>95</td>
<td>45</td>
<td>100(95)*</td>
<td>16.20</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>II</td>
<td>Fossil</td>
<td>200</td>
<td>95</td>
<td>400</td>
<td>100(95)</td>
<td>5.50</td>
<td>200(190)</td>
<td>4.25</td>
</tr>
<tr>
<td>III</td>
<td>Nuclear</td>
<td>300</td>
<td>90</td>
<td>228</td>
<td>100(90)</td>
<td>2.28</td>
<td>300(270)</td>
<td>1.90</td>
</tr>
<tr>
<td>IV</td>
<td>Fossil</td>
<td>600</td>
<td>90</td>
<td>1440</td>
<td>200(180)</td>
<td>3.92</td>
<td>600(540)</td>
<td>3.32</td>
</tr>
<tr>
<td>V</td>
<td>Nuclear</td>
<td>800</td>
<td>85</td>
<td>432</td>
<td>300(255)</td>
<td>2.25</td>
<td>800(680)</td>
<td>1.71</td>
</tr>
</tbody>
</table>

*(95MW) = 0.95 x 100 MW = $K_{ri}$ for Example 2 only.

\[ P_r \times K_{ri} \]
Figure C.1

Normalized Customer Load-Duration Curve for 730 Hour Month on Reference Utility System

- Minimum demand 800 MW
- $D_T = 949 \text{ MWH}$
- 0.80 at 1200 MW
- 0.20 at 1400 MW
- Peak demand 1800 MW
- Installed capacity 2000 MW

$F$, probability ($P_z$)

$P$, load (MW)
Table C.2

SYSINT Fortran-to-Text Symbol Cross-Reference Table

<table>
<thead>
<tr>
<th>SYSINT Fortran Symbol</th>
<th>Text Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVPROB</td>
<td>$\frac{1}{\Delta K_{ri}} \int_{P_{ri}}^{P_{ri}^0 + \Delta K_{ri}} F_{ri}(P_e) dP_e$</td>
<td>Average availability-based capacity factor for the capacity increment</td>
</tr>
<tr>
<td></td>
<td>$E_{ri} = \frac{E_{ri}}{K_{ri} T_{p ri}} = L'_{ri}$</td>
<td></td>
</tr>
<tr>
<td>DELGWH</td>
<td>$E_{ri}$</td>
<td>Increment energy production, GWH</td>
</tr>
<tr>
<td>DM</td>
<td></td>
<td>Spacing of F array stored in PROB.</td>
</tr>
<tr>
<td>EXPGWH</td>
<td>$\Sigma E_{ri}$</td>
<td>Cumulative increment production, GWH</td>
</tr>
<tr>
<td>IDNO</td>
<td></td>
<td>Unit identification number</td>
</tr>
<tr>
<td>IEMAX</td>
<td></td>
<td>PROB storage location of peak equivalent load, PROB(IEMAX) $\equiv 0.0$</td>
</tr>
<tr>
<td>L</td>
<td>$r$</td>
<td>Unit index = order unit data read in = order final unit results presented</td>
</tr>
<tr>
<td>MWADD</td>
<td>$\Delta K_{ri}$</td>
<td>Increment of capacity being loaded for unit-of-interest $r$</td>
</tr>
</tbody>
</table>
Table C.2--Continued

<table>
<thead>
<tr>
<th>SYSINT Fortran Symbol</th>
<th>Text Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWIN</td>
<td>$K_{r,i-1}$</td>
<td>Unit r capacity previously loaded.</td>
</tr>
<tr>
<td>MWTOT</td>
<td>$K_{ri}$</td>
<td>Unit r capacity now loaded</td>
</tr>
<tr>
<td>PE</td>
<td>$P_{ri}^o + \Delta K_{ri}$</td>
<td>Equivalent load after loading increment</td>
</tr>
<tr>
<td>PROB(K)</td>
<td>$F_{ri}(P_e=K*DM)$</td>
<td>Current F equivalent load-duration curve</td>
</tr>
</tbody>
</table>

Position in loading order
Table C.3

Example 1 on Reference Utility System: "Deterministic Model (No Forced-Outages)"

(See Sect. 2.2.1 for further details.)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Increment</th>
<th>Position in Loading Order</th>
<th>Increment Energy $E_{ri}$ (GWH)</th>
<th>Increment Cost $X_{ri}$ $(10^3 $)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>9 (last)</td>
<td>-0-</td>
<td>-0-</td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>4</td>
<td>73.00</td>
<td>401.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
<td>-0-</td>
<td>-0-</td>
</tr>
<tr>
<td>III</td>
<td>1</td>
<td>2</td>
<td>73.00</td>
<td>166.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6</td>
<td>73.00</td>
<td>138.7</td>
</tr>
<tr>
<td>IV</td>
<td>1</td>
<td>3</td>
<td>146.00</td>
<td>572.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7</td>
<td>29.20</td>
<td>97.0</td>
</tr>
<tr>
<td>V</td>
<td>1</td>
<td>1 (first)</td>
<td>219.00</td>
<td>492.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5</td>
<td>335.80</td>
<td>574.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Utility Production 949.00</td>
<td>2442.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Emergency Purchases (at 10$/MWH) -0-</td>
<td>-0-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total 949.00</td>
<td>2442.9</td>
</tr>
</tbody>
</table>

Loss-of-Load Probability, LOLP = 0%
## Table C.4

### Example 1: SYSINT Output Totals

<table>
<thead>
<tr>
<th>INDEX</th>
<th>IDNU</th>
<th>NAME</th>
<th>LFACT</th>
<th>CPER HRS</th>
<th>STARTUPS &amp; SHUTDCWS</th>
<th>ELECTR (GWH)</th>
<th>MEGABTU</th>
<th>COST ($)</th>
<th>INCL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>101</td>
<td>I 0.6</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>102</td>
<td>II 0.90000</td>
<td>0.90000</td>
<td>0.90000</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>103</td>
<td>III 0.70000</td>
<td>0.70000</td>
<td>0.70000</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>104</td>
<td>IV 0.80000</td>
<td>0.80000</td>
<td>0.80000</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>105</td>
<td>V 0.50000</td>
<td>0.50000</td>
<td>0.50000</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

### Power:
- Installate Capacity: 2000 MEGAWATTS
- Line-load Capacity: 2000 MEGAWATTS
- Peak Load: 1800 MEGAWATTS
- On-line Margin & Peak: 300 MEGAWATTS
- Spinning Reserve: 0 MEGAWATTS
- LCSS-CF-Lead PRCAPABILITY: 0.0 MEGAWATTS

### Energy:
- Expected Demand: 2442072.9 GWH
- Expected Production: 2442072.9 MEGAWATTS
  - Nuclear: 1372108.4 MEGAWATTS
  - Non-nuclear: 1070764.5 MEGAWATTS
- Expected Emerg. Punch: 0.0 MEGAWATTS
- Conserved by Direct Calc: J.J. 1

### Dollar Costs:
- Production Fuel: 2442072.9
- Startups & Shutdowns: 0
- Sub-totals: 2442072.9
- Emerg. Punch: 1.00 $/MWH
- Total: 2442072.9
# Table C.5

**Example 1: SYSINT Detailed Calculations**

<table>
<thead>
<tr>
<th>L</th>
<th>SECU</th>
<th>PE</th>
<th>MAIS</th>
<th>INOC</th>
<th>D PPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- L: Location
- SECU: Security Unit
- PE: Process Equipment
- MAIS: Material Identification System
- INOC: Input Operating Conditions
- D PPM: Design Pressure

**Example Data:**
- Location: 1
- Security Unit: 1
- Process Equipment: 1
- Material Identification System: 1
- Input Operating Conditions: 1
- Design Pressure: 1

**Further Details:**
- Additional calculations and data points are available in the table format above.
- The table includes various parameters and values relevant to the SYSINT calculations.
- Each row represents a specific parameter set for calculation purposes.

---

**Example Calculations:**
- Example 1 demonstrates the detailed calculations for a SYSINT system.
- The table format is used to organize and present the data clearly.
- Each row corresponds to a different scenario or set of conditions.

---

**Additional Resources:**
- Further technical documentation is available for detailed analysis and understanding of the SYSINT system calculations.
- The table format is optimized for readability and ease of use in technical reporting and presentations.

---
Example 2 on Reference Utility System: "Deterministic Model (Reduced Capacities)"

(See Sect. 2.2.1 for further details.)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Increment</th>
<th>Position in Loading Order</th>
<th>Increment Energy $E_{ri}$ (GWH)</th>
<th>Increment Cost $X_{ri}$ ($10^3$ $$$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>9</td>
<td>2.51</td>
<td>40.7</td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>4</td>
<td>69.35</td>
<td>381.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
<td>5.81</td>
<td>24.7</td>
</tr>
<tr>
<td>III</td>
<td>1</td>
<td>2</td>
<td>65.70</td>
<td>149.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6</td>
<td>108.82</td>
<td>206.8</td>
</tr>
<tr>
<td>IV</td>
<td>1</td>
<td>3</td>
<td>131.40</td>
<td>515.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7</td>
<td>79.85</td>
<td>265.1</td>
</tr>
<tr>
<td>V</td>
<td>1</td>
<td>1</td>
<td>186.15</td>
<td>418.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5</td>
<td>299.30</td>
<td>511.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Utility Production</td>
<td>948.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Emergency Purchases (at 10$/MWH)</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>949.00</td>
</tr>
</tbody>
</table>

Loss-of-Load Probability, LOLP = 1.25%
### Table C.7

#### Example 2: SYSINT Output Totals

<table>
<thead>
<tr>
<th>STRATEGY ID</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>PERICE NUMBER</td>
<td>1</td>
</tr>
<tr>
<td>TITLE</td>
<td>EXAMPLE NO. 2: DETERMINISTIC MODEL (REDUCED CAPACITIES)</td>
</tr>
</tbody>
</table>

| INDEX | LOAD | NAME | LD FACT | CPU PER MRS | STARTUPS & SHUTDOWN | ELECTRIC | PRODUCTION | MEGAWATT | COST ($) | MEGAWATT | COST ($) | TOTALS | MEGAWATT | COST ($) | INDEX |
|-------|------|------|---------|-------------|---------------------|----------|------------|-----------|----------|----------|----------|--------|---------|----------|----------|-------|
| 1     | 101  | I    | 0.0336250 | 26.442625 | 0.4440              | 22.0.20   | 2.5139%   | 4525.1    | 40726.1  | 4523.1   | 40734.1  | 1      |
| 2     | 202  | II   | 0.244875  | 700.0000  | 0.0000              | 0.0.0    | 75.1596% | 8122.9%   | 40610.9  | 81221.9  | 40613.9  | 2      |
| 3     | 303  | III  | 0.482243  | 700.0000  | 0.0000              | 0.0.3   | 174.52019 | 1876.6022 | 3565.94  | 18766.2   | 35665.4  | 3      |
| 4     | 404  | IV   | 0.533891  | 700.0000  | 0.0000              | 0.0.0   | 211.24831 | 1950.461   | 7801.84  | 19504.6   | 78018.4  | 4      |
| 5     | 505  | V    | 0.577932  | 700.0000  | 0.0000              | 0.0.0   | 485.44544 | 5170.182   | 9336.33  | 51731.8   | 93363.3  | 5      |

#### Power:

- **INSTALLED CAPACITY**: 1775
- **MIN-LINE CAPACITY**: 1375
- **PEAK LOAD FORECAST**: 1800
- **CA-LINE MARGIN & PEAK**: -25
- **SPINNING RESERVE**: 0
- **LCSS-CF-LOAD PRODABILITY**: 0.012500

#### Energy:

- **EXPECTED DEMAND**: 949.1000
- **EXPECTED PRODUCTION**: 949.1000
- **NUCLEAR**: 659.9956
- **ENHANCED-NUCLEAR**: 289.1000
- **EXPECTED DUES PURCHASE**: 0.0000
- **LASERED BY DIRECT CALC**: 0.0000

#### Dollar Cost:

- **SYSTEM**: 2514.02
- **NUCLEAR**: 1287.187
- **ENHANCED-NUCLEAR**: 12270.19
- **STARTUPS & SHUTDOWNS**: 2514.02
- **SUR-TOTALS**: 2514.02
- **TOTAL**: 2514.02
### Table C.8

**Example 2: SYSINT Detailed Calculations**

<table>
<thead>
<tr>
<th>L</th>
<th>NAME</th>
<th>PM</th>
<th>MAP</th>
<th>PIECE</th>
<th>RELAY</th>
<th>IPMEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note: The table continues with similar entries.*

---

**Example 2 (continued)**

```
Example 2: SYSINT Detailed Calculations

1. L: NAME, PM, MAP, PIECE, RELAY, IPMEN

<table>
<thead>
<tr>
<th>L</th>
<th>NAME</th>
<th>PM</th>
<th>MAP</th>
<th>PIECE</th>
<th>RELAY</th>
<th>IPMEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

   *Note: The table continues with similar entries.*
```
Example 3 on Reference Utility System: "Probabilistic Model (With Forced-Outages)"

(See Sect. 2.2.1 for further details.)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Increment</th>
<th>Position in Loading Order</th>
<th>Increment Energy $E_{ri}$ (GWH)</th>
<th>Increment Cost $X_{ri}$ ($10^3$ $$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>9</td>
<td>11.93</td>
<td>193.3</td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>4</td>
<td>69.35</td>
<td>381.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
<td>14.01</td>
<td>59.5</td>
</tr>
<tr>
<td>III</td>
<td>1</td>
<td>2</td>
<td>65.70</td>
<td>149.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6</td>
<td>80.69</td>
<td>153.3</td>
</tr>
<tr>
<td>IV</td>
<td>1</td>
<td>3</td>
<td>131.40</td>
<td>515.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7</td>
<td>70.85</td>
<td>235.2</td>
</tr>
<tr>
<td>V</td>
<td>1</td>
<td>1</td>
<td>186.15</td>
<td>418.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5</td>
<td>288.81</td>
<td>493.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Utility Production</td>
<td>918.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Emergency Purchases (at 10$/\text{MWH}$)</td>
<td>30.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>949.00</td>
</tr>
</tbody>
</table>

Loss-of-Load Probability, LOLP = 15.6%
### Table C.10: Example 3: SYSINT Output Totals

<table>
<thead>
<tr>
<th>STRATEGY ID</th>
<th>2</th>
<th>TITLE: SAMPLE SYSINT RUN PERFORMING CALCS. FOR EXAMPLES 3 THRU 5</th>
<th>PERIOD NUMBER</th>
<th>1</th>
<th>TITLE: EXAMPLE NO. 3: PROBABILISTIC MODEL (WITH FORCED-CUTAGES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>INDEX</td>
<td>IDNO</td>
<td>NAME</td>
<td>LOAD FACT</td>
<td>CPER HRS</td>
<td>STARTUPS &amp; SHUTDOWNS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NUMBER</td>
</tr>
<tr>
<td>1</td>
<td>L01</td>
<td>I</td>
<td>0.103473</td>
<td>119.3353</td>
<td>4.591</td>
</tr>
<tr>
<td>2</td>
<td>L02</td>
<td>II</td>
<td>0.756922</td>
<td>613.7500</td>
<td>0.376</td>
</tr>
<tr>
<td>3</td>
<td>L03</td>
<td>III</td>
<td>0.608420</td>
<td>657.0000</td>
<td>0.669</td>
</tr>
<tr>
<td>4</td>
<td>L04</td>
<td>IV</td>
<td>0.641762</td>
<td>657.0000</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>L05</td>
<td>V</td>
<td>0.613251</td>
<td>620.5000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

**F C W E R:**
- MEGAWATTS
  - INSTALLED CAPACITY: 2030
  - ON-LINE CAPACITY: 2030
  - PEAK LOAD FORECAST: 1800

**E N E R G Y:**
- GWH
  - EXPECTED DEMAND: 949.0000
  - EXPECTED DEMAND (NUCLEAR): 918.0000
  - EXPECTED DEMAND (NON-NUCLEAR): 121.5000
  - EXPECTED EMERG PURCH (UNSERVED BY DIRECT CALC): 30.1112

**C O U N T R Y:**
- SYSTEM: 2600.004
  - NUCLEAR: 1215.004
  - NON-NUCLEAR: 1384.000
  - SUB-TOTALS: 2600.004
  - EMERG PURCH: 13.00 $/MMBtu: 30.1112
  - TOTAL: 2901.115
### Table C.11: Example 3: SYSINT Detailed Calculations

<table>
<thead>
<tr>
<th>PL</th>
<th>FL</th>
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<th>Phase</th>
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</table>

**Notes:**
- PL: Plant
- FL: Field
- PASS: Passage
- Phase: Phase of operation
- NAME: Name of the parameter
- VALUE: Value of the parameter
Table C.12

Example 4 on Reference Utility System:
"Single Increment Booth-Baleriaux Model"
(See Sect. 3.3.1.3 for further details.)

<table>
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<tr>
<th>Unit</th>
<th>Increment</th>
<th>Position in Loading Order</th>
<th>Increment Energy $E_{ri}$ (GWH)</th>
<th>Increment Cost $X_{ri}$ ($10^3$ $)</th>
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</thead>
<tbody>
<tr>
<td>I-I</td>
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<td>11.93</td>
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<td>2</td>
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<td>195.17</td>
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<td></td>
</tr>
<tr>
<td>V</td>
<td>1</td>
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<td>496.40</td>
<td>949.4</td>
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<td></td>
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</table>

Utility Production 918.89 2380.5
Emergency Purchases (10 $$/MWH) 30.11 301.1

Total 949.00 2681.6

Loss-of-load Probability, LOLP = 15.6%
### Example 4: SYSINT Output Totals

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<th>PERIOD NUMBER =</th>
<th>2</th>
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</table>

#### STRATEGY IC = 2

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</table>

<table>
<thead>
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<th>IC</th>
<th>NAME</th>
<th>LC FACT</th>
<th>STARTUPS &amp; SHUTDOWNS</th>
<th>ELECT(GWH</th>
<th>MEGABTU</th>
<th>COST($)</th>
<th>MEGABTU</th>
<th>COST($)</th>
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<td>215.033 193.530</td>
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<td>160.9425 6.1273 650 251</td>
<td>30.85035 350.439 152 313</td>
<td>310.840 153.542</td>
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<td></td>
<td></td>
</tr>
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<td>IC</td>
<td>III</td>
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<td>527.425 949.365</td>
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</tbody>
</table>

#### POWER:

- **INSTALLED CAPACITY**: 2000 MW
- **CN-LINE CAPACITY**: 2000 MW
- **PEAK LOAD FORECAST**: 1600 MW
- **CN-LINE MARGIN & PEAK**: 2000 MW
- **SPINNING RESERVE**: 0.15647 MW
- **LCSS-OF-LOAD PROBABILITY**: 0.15647

#### Energy:

- **EXPECTED DEMAND**: 949.150 MW
- **EXPECTED PRODUCTION**: 918.800 MW
- **NUCLEAR**: 680.934 MW
- **NCN-NUCLEAR**: 237.955 MW
- **EXPECTED EMERG PURCH**: 30.1112 MW
- **UNSERVED BY DIRECT CALC**: 30.1112 MW

#### CELLAR COST:

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>PRODUCTION FUEL</th>
<th>STARTUPS &amp; SHUTDOWNS</th>
<th>STARTUPS &amp; SHUTDOWNS</th>
<th>TOTAL</th>
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</thead>
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Example 5 on Reference Utility System:

"Multiple Increment Booth-Baleriaux Model (V-2, then III-2)"

(Among Nuclear Upper Increments V-2, then III-2)

(See Sect. 3.3.2.1 for further details.)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Increment</th>
<th>Position in Loading Order</th>
<th>Increment Energy $E_{ri}$ (GWH)</th>
<th>Increment Cost $X_{ri}$ $(10^3 , $)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
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<td>11.93</td>
<td>193.3</td>
</tr>
<tr>
<td>II</td>
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<td>36.71</td>
<td>201.9</td>
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<tr>
<td></td>
<td>2</td>
<td>8</td>
<td>14.01</td>
<td>59.5</td>
</tr>
<tr>
<td>III</td>
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<td>2</td>
<td>65.70</td>
<td>149.8</td>
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<tr>
<td>(Nuclear)</td>
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<td>5</td>
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<tr>
<td>IV</td>
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<td>515.1</td>
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<td>2</td>
<td>7</td>
<td>70.85</td>
<td>235.2</td>
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<tr>
<td>V</td>
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<td>(Nuclear)</td>
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Utility Production: 918.89  2481.0
Emergency Purchases (10 \$/MWH): 30.11  301.1

Total: 949.00  2782.1

Loss-of-load Probability, LOLP = 15.6%
### Table C.16

**Example 5: SYSINT Output Totals**

| STRATEGY ID | TITLF: "SAMPLE SYSINT RUN PERFORMING CALCS. FOR EXAMPLES 3 THRU 5" | PERICY NUMBER | TITLF: "EXAMPLE NO. 5: MULTIPLE INCREMENT BOTH-MATRIX MODEL (V-2, THEN III-2)"
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<td>4D4</td>
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<td>5MS</td>
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**POWER:**

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<th>MEGAWATTS</th>
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</table>

**IN-LINE CAPACITY:**

| PEAK LOAD FORECAST | 1800 |
| SPINNING RESERVE   | 80   |
| CLSS-CF-LCAD P.RABILITY | 0.156470 |

**ENERGY:**

| EXPECTED DEPARE | 949.300J |
| EXPECTED PRODUCTION | 918.8688 |
| (NUCLEAR) | 653.4966 |
| (NON-NUCLEAR) | 264.8592 |
| EXPECTED EMERG PURCH | 30.1112 |
| (UNSERVED BY DIRECT CALC) | 30.1112 |

**COLLAR COST:**

| SYSTEM | NUCLEAR | NON-NUCLEAR |
| PRODUCTION FUEL | 2481090. | 1276033. | 1285058. |
| STARTUPS & SHUTDOWNS | 300850. | 100125. | 193720. |
| SUB-TOTALS | 2491050. | 1276033. | 1285058. |
| EMERG PURCH @ 10.00 $/MWh | 301112. | | |
| TOTAL | 2792812. | | |
### Table C.17

**Example 5: SYSINT Detailed Calculations**

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<th>Mach</th>
<th>Method</th>
<th>Notes</th>
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<td>2</td>
<td>0</td>
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</table>
Example 6 on Reference Utility System:

"Multiple Increment Booth-Baleriaux Model (III-2, then V-2)"

(Among Nuclear Upper Increments III-2, then V-2)

(See Sect. 3.3.3 for further details.)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Increment</th>
<th>Position in Loading Order</th>
<th>Increment Energy $E_{ri}$ (GWH)</th>
<th>Increment Cost $X_{ri}$ ($10^3$ $$$)</th>
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<tr>
<td>I</td>
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<td>11.93</td>
<td>193.3</td>
</tr>
<tr>
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<td>36.71</td>
<td>201.9</td>
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Utility Production $918.89$ $2486.3$
Emergency Purchases (10 $$/MWH) $30.11$ $301.1$

Total $949.00$ $2787.4$

Loss-of-load Probability, LOLP = 15.6%
## Table C.19

**Example 6: SYSINT Output Totals**

### Perforomance Calculations: SEC I-2, Then V-2

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<th>ICNO</th>
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<th>LOAD FACT</th>
<th>OPER HRS</th>
<th>STARTUPS &amp; SHUTDOWNS</th>
<th>EXPECTED PRODUCTION</th>
<th>TOTALS</th>
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<th>OPER HRS</th>
<th>STARTUPS &amp; SHUTDOWNS</th>
<th>EXPECTED PRODUCTION</th>
<th>TOTALS</th>
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<td>401302.0852</td>
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</table>

### POWER
- **Installed Capacity**: 2000
- **On-Load Capacity**: 1000
- **Peak Load Forecast**: 1000
- **Spinning Reserve**: 2000

### ENERGY
- **Expected Demand**: 94500000
- **Expected Production**: 24966860
  - **Nuclear**: 12302250
  - **Non-Nuclear**: 20666635
- **Expected Emerg. Repl. (Unserved MW Direct Loss)**: 331112

### COLLAR COST
- **System**: 24966860
- **Nuclear**: 12302250
- **Non-Nuclear**: 12664610
- **Sub-Total**: 24966860
- **Emerg. Purch. @ 10.00 $/MM$: 2013322
- **Total**: 24966860

### VLA
- **Installed Capacity**: 2000
- **On-Load Capacity**: 1000
- **Peak Load Forecast**: 1000
- **Spinning Reserve**: 2000

### Expected DEMAND
- **Nuclear**: 12302250
- **Non-Nuclear**: 20666635

### Expected Production
- **Nuclear**: 12302250
- **Non-Nuclear**: 20666635

### Expected Emerg. Repl. (Unserved MW Direct Loss)
- **System**: 331112
### Table C.20

**Example 6: SYSINT Detailed Calculations**

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<th>Value 2</th>
<th>Value 3</th>
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APPENDIX D
NUMERICAL RESULTS FOR CASES I THROUGH VI ON HYPOTHETICAL UTILITY SYSTEM OF CHAPTER 5

Section 5.3 presented the customer loads, generating equipment and the three maintenance and refueling strategies investigated. (Figures D.1 to D.3 present the reactor-cycle notation used in tabulating the results for each strategy). Section 5.4 indicated the values chosen for the remaining parameters of interest. Table 5.8 presented the structure of the Case I through VI studies.

Tables D.1 through D.6 present the same Case-by-Case results presented throughout Chapter 5. In addition, Table D.7 presents the Case I results at the end of the first shape iteration when $\overline{TC} = \overline{TC}^*,0$. These results differ from Case II input only with respect to the planning horizon (72 month rather than 48 month as in Case II).

Tables D.8-D.25 present strategy-by-strategy, Case-by-Case detailed results for each reactor-cycle. In addition, Tables D.26-D.28 present Case I strategy-by-strategy data at the end of the first shape iteration.
Figure D.1

Reactor-Cycle Notation for Strategy 1 (Annual Refuelings)

TIME (YEARS)

A
A-1 A-2 A-3 A-4 A-5 A-6 A-7
B B-2 B-3 B-4 B-5 B-6 B-7
C C-1 C-2 C-3 C-4 C-5 C-6
D D-1 D-2 D-3 D-4 D-5 D-6 D-7
E E-1 E-2 E-3 E-4 E-5 E-6
F F-1 F-2 F-3

SUMMER MONTHS
TWO MONTH REFUELING
Figure D.2

Reactor-Cycle Notation for Strategy 2 (Gradual Shift to Longer Cycles)

TIME (YEARS)

0 1 2 3 4 5 6
Figure D.3
Reactors-Cycle Notation for Strategy 3 (Immediate Shift to Longer Cycles)
TABLE D.1  
REVENUE REQUIREMENTS AND UNDISCOUNTED  
ENERGY FOR CASE I  
(72 Month Horizon, 7% P.V. Rate, Reference Nuclear Unit Costs,  
0.0 Shape Rejection Criterion)  
Direct Calculation Using $\gamma = 0.25$

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<tr>
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<th>S-2</th>
<th>S-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downtime to horizon (reactor-months)</td>
<td>62</td>
<td>51</td>
<td>49</td>
</tr>
<tr>
<td>Average cycle length (months)</td>
<td>12</td>
<td>14.9</td>
<td>15.2</td>
</tr>
<tr>
<td>System nuclear capacity factor</td>
<td>0.642</td>
<td>0.656</td>
<td>0.658</td>
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<td></td>
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<td>$10^6$ MWH</td>
<td>$10^6$ MWH</td>
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<tr>
<td>Fossil fuel</td>
<td>293.205</td>
<td>276.853</td>
<td>274.082</td>
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<tr>
<td>(90.068)</td>
<td>(85.836)</td>
<td>(85.196)</td>
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<tr>
<td>Startup-shutdown cost</td>
<td>2.022</td>
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<td>1.650</td>
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<td>Emergency purchases</td>
<td>0.655</td>
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<td>0.363</td>
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<td>(0.079)</td>
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<td>Nonnuclear production</td>
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<td>(189.814)</td>
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</tr>
<tr>
<td>Downtime to horizon (reactor-months)</td>
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<td>31</td>
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<tr>
<td>Average cycle length (months)</td>
<td>12</td>
<td>14.5</td>
<td>15.2</td>
</tr>
<tr>
<td>System nuclear capacity factor</td>
<td>0.638</td>
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<td>0.651</td>
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\[10^6 \text{ $} (10^6 \text{ MWH})\]

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<th>S-1</th>
<th>S-2</th>
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<td>1.227</td>
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<tr>
<td>Emergency purchases</td>
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TABLE D.3
REVENUE REQUIREMENTS AND UNDISCOUNTED ENERGY FOR CASE III
(48 Month Horizon, 0% P.V. Rate, Reference Nuclear Unit Costs, No Shape Constraints)

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<th>S-3</th>
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<td>System nuclear capacity factor</td>
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<td>0.647</td>
<td>0.651</td>
</tr>
</tbody>
</table>

|                     | 10^6$     |
|                     | (10^6 MWH) |
| Fossil fuel         | 212.434   |
|                    | (51.703)  |
| Startup-shutdown cost | 1.684    |
| Emergency purchases | 0.528     |
|                    | (0.053)   |
| Nonnuclear production | 214.646  |
|                    | (51.756)  |
| Nuclear fuel        | 158.416   |
|                    | (118.376) |
| System production   | 373.062   |
|                    | (170.132) |
| Fixed firm purchase | 108.624   |
|                    | (54.312)  |
| Penalty for short-notice enrichment changes | 2.000 |
| System Total        | 481.686   |
|                    | (224.444) |
### Table D.4

**Revenue Requirements and Undiscounted Energy for Case IV**

(48 Month Horizon, 12% P.V. Rate, Reference Nuclear Unit Costs, No Shape Constraints)

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<td>31</td>
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<td>Average cycle length (months)</td>
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<td>15.2</td>
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<td>System nuclear capacity factor</td>
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<td>0.647</td>
<td>0.651</td>
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$10^6$ $(10^6 \text{ MWH})$

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<td>1.388</td>
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<td>(0.030)</td>
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**TABLE D.5**
REVENUE REQUIREMENTS AND UNDISCOUNTED ENERGY FOR CASE V
(48 Month Horizon, 7% P.V. Rate, Low Nuclear Unit Costs, No Shape Constraints)

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<td>Average cycle length (months)</td>
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<tr>
<td>System nuclear capacity factor</td>
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<td>0.647</td>
<td>0.651</td>
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<table>
<thead>
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<tr>
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<td>184.223</td>
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<td>173.250</td>
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<td>(50.061)</td>
<td>(49.390)</td>
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<td>Startup-shutdown cost</td>
<td>1.497</td>
<td>1.281</td>
<td>1.227</td>
</tr>
<tr>
<td>Emergency purchases</td>
<td>0.464</td>
<td>0.317</td>
<td>0.265</td>
</tr>
<tr>
<td></td>
<td>(0.053)</td>
<td>(0.036)</td>
<td>(0.030)</td>
</tr>
<tr>
<td>Nonnuclear production</td>
<td>186.184</td>
<td>177.946</td>
<td>174.742</td>
</tr>
<tr>
<td></td>
<td>(51.756)</td>
<td>(50.097)</td>
<td>(49.420)</td>
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<td>143.463</td>
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<td>(120.712)</td>
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<tr>
<td>Penalty for short-notice enrichment changes</td>
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<td></td>
<td>2.000</td>
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</table>

| System Total                      | 422.579      | 414.268      | 415.371      |
|                                  | (224.444)    | (224.444)    | (224.444)    |
### TABLE D.6

**REVENUE REQUIREMENTS AND UNDISCOUNTED ENERGY FOR CASE VI**

(48 Month Horizon, 7% P.V. Rate, High Nuclear Unit Costs, No Shape Constraints)

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<th>S-3</th>
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<td>33</td>
<td>31</td>
</tr>
<tr>
<td>Average cycle length (months)</td>
<td>12</td>
<td>14.5</td>
<td>15.2</td>
</tr>
<tr>
<td>System nuclear capacity factor</td>
<td>0.638</td>
<td>0.647</td>
<td>0.651</td>
</tr>
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</table>

\[
\begin{array}{c|c|c|c}
|                     & 10^6\$ &       &       \\
|                     & (10^6 MWH) &       &       \\
<p>|---------------------&amp;-----------|-------|-------|
| Fossil fuel         | 184.223   | 176.348| 173.250|
|                     | (51.703)  | (50.061)| (49.390)|
| Startup-shutdown cost| 1.497     | 1.281  | 1.227 |
| Emergency purchases | 0.464     | 0.317  | 0.265 |
|                     | (0.053)   | (0.036)| (0.030)|
| Nonnuclear production| 186.184   | 177.946| 174.742|
|                     | (51.756)  | (50.097)| (49.420)|
| Nuclear fuel        | 255.223   | 253.211| 256.169|
|                     | (118.376) | (120.035)| (120.712)|
| System production   | 441.407   | 431.157| 430.911|
|                     | (170.132) | (170.132)| (170.132)|
| Fixed firm purchase | 95.166    | 95.166 | 95.166 |
|                     | (54.312)  | (54.312)| (54.312)|
| Penalty for short-notice enrichment changes  |         |       | 2.000 |
| System Total        | 536.573   | 526.323| 528.077|
|                     | (224.444) | (224.444)| (224.444)|</p>
<table>
<thead>
<tr>
<th>Strategy</th>
<th>S-1</th>
<th>S-2</th>
<th>S-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downtime to horizon (reactor-months)</td>
<td>62</td>
<td>51</td>
<td>49</td>
</tr>
<tr>
<td>Average cycle length (months)</td>
<td>12</td>
<td>14.9</td>
<td>15.2</td>
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<td>System nuclear capacity factor</td>
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<td>0.658</td>
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<td></td>
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<tr>
<td><strong>(10^6 MWH)</strong></td>
<td></td>
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</tr>
<tr>
<td>Fossil fuel</td>
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<td>276.853</td>
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<td>(85.836)</td>
<td>(85.196)</td>
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<td>Startup-shutdown cost</td>
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<td>(0.079)</td>
<td>(0.048)</td>
<td>(0.043)</td>
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<td>(85.884)</td>
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<td>Nuclear fuel</td>
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<td></td>
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<td>(194.077)</td>
<td>(194.722)</td>
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<td>(279.961)</td>
<td>(279.961)</td>
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<td>Penalty for short-notice enrichment changes</td>
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<td><strong>System Total</strong></td>
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**TABLE D. 8**

**REACTOR-CYCLE RESULTS FOR STRATEGY 1 IN CASE I**

(72 Month Horizon, 7% P.V. Rate, Reference Nuclear Unit Costs, \( V^2_{REJ} = 0 \))

<table>
<thead>
<tr>
<th>Reactor-Cycle</th>
<th>Cycle Length (Months on-line)</th>
<th>Cycle Energy (GWH)</th>
<th>Average Cycle Energy Cost ($/MWH)</th>
<th>Incremental Cycle Energy Cost ($/MWH)</th>
<th>Reload Enrichment (w/o U-235)</th>
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<td>A-1</td>
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<td>.992</td>
<td>2.876</td>
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</tr>
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<td>638</td>
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<td>.499</td>
<td>-</td>
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<td>-</td>
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<td>.683</td>
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<td>6060</td>
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<td>.992</td>
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<td>2.086</td>
<td>.992</td>
<td>1.5**</td>
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</table>

* Fractional cycle
† Fixed initial condition
** 1.5 w/o U-235 was lower limit permitted by QKCORE.
### TABLE D. 9

**REACTOR-CYCLE RESULTS FOR STRATEGY 2 IN CASE I**

(72 Month Horizon, 7% P.V. Rate, Reference Nuclear Unit Costs, $V_{REJ}^2 = 0$)

<table>
<thead>
<tr>
<th>Reactor-Cycle</th>
<th>Cycle Length (Months on-line)</th>
<th>Cycle Energy (GWH)</th>
<th>Average Cycle Energy Cost ($/MWH)</th>
<th>Incremental Cycle Energy Cost ($/MWH)</th>
<th>Reload Enrichment (w/o U-235)</th>
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<td>.959</td>
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<td>1.408</td>
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<td>3.650</td>
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<td>.959</td>
<td>3.6†</td>
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* Fractional cycle
† Fixed initial condition
TABLE D. 10
REACTOR-CYCLE RESULTS FOR STRATEGY 3 IN CASE I
(72 Month Horizon, 7% P.V. Rate, Reference Nuclear Unit Costs, $^2_{REJ} = 0$)

<table>
<thead>
<tr>
<th>Reactor-Cycle</th>
<th>Cycle Length (Months on-line)</th>
<th>Cycle Energy (GWH)</th>
<th>Average Cycle Energy Cost ($/MWH)</th>
<th>Incremental Cycle Energy Cost ($/MWH)</th>
<th>Reload Enrichment (w/o U-235)</th>
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</thead>
<tbody>
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* Fractional cycle
† Fixed initial condition
** Short notice enrichment change (5.0 w/o U-235 was upper limit permitted by QKCORE).
## TABLE D. 11
### REACTOR-CYCLE RESULTS FOR STRATEGY 1 IN CASE II

(48 Month Horizon, 7% P.V. Rate,
Reference Nuclear Unit Costs, No Shape Constraints)

<table>
<thead>
<tr>
<th>Reactor-Cycle</th>
<th>Cycle Length (Months on-line)</th>
<th>Cycle Energy (GWH)</th>
<th>Average Cycle Energy Cost ($/MWH)</th>
<th>Incremental Cycle Energy Cost ($/MWH)</th>
<th>Reload Enrichment (w/o U-235)</th>
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* Fractional cycle  
† Fixed initial condition  
** 1.5 w/o U-235 was lower limit permitted by QKCORE.
### TABLE D. 12
REACTOR-CYCLE RESULTS FOR STRATEGY 2 IN CASE II
(48 Month Horizon, 7% P.V. Rate, Reference Nuclear Unit Costs, No Shape Constraints)

<table>
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<tr>
<th>Reactor-Cycle</th>
<th>Cycle Length (Months on-line)</th>
<th>Cycle Energy (GWH)</th>
<th>Average Cycle Energy Cost ($/MWH)</th>
<th>Incremental Cycle Energy Cost ($/MWH)</th>
<th>Reload Enrichment (w/o U-235)</th>
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* Fractional cycle
† Fixed initial condition
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<th>Reactor-Cycle</th>
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<th>Cycle Energy (GWH)</th>
<th>Average Cycle Energy Cost ($/MWH)</th>
<th>Incremental Cycle Energy Cost ($/MWH)</th>
<th>Reload Enrichment (w/o U-235)</th>
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* Fractional cycle
† Fixed initial condition
** Short-notice enrichment change (5.0 w/o U-235 was upper limit permitted by QKCORE).
TABLE D. 14
REACTOR-CYCLE RESULTS FOR STRATEGY 1 IN CASE III
(48 Month Horizon, 0% P.V. Rate,
Reference Nuclear Unit Costs, No Shape Constraints)

<table>
<thead>
<tr>
<th>Reactor-Cycle</th>
<th>Cycle Length (Months on-line)</th>
<th>Cycle Energy (GWH)</th>
<th>Average Cycle Energy Cost ($/MWH)</th>
<th>Incremental Cycle Energy Cost ($/MWH)</th>
<th>Reload Enrichment (w/o U-235)</th>
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<tbody>
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* Fractional cycle
† Fixed initial condition
** 1.5 w/o U-235 was lower limit permitted by QKCORE.
### TABLE D. 15
REACTOR-CYCLE RESULTS FOR STRATEGY 2 IN CASE III
(48 Month Horizon, 0% P.V. Rate, Reference Nuclear Unit Costs, No Shape Constraints)

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<tr>
<th>Reactor-Cycle</th>
<th>Cycle Length (Months on-line)</th>
<th>Cycle Energy (GWH)</th>
<th>Average Cycle Energy Cost ($/MWH)</th>
<th>Incremental Cycle Energy Cost ($/MWH)</th>
<th>Reload Enrichment (w/o U-235)</th>
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* Fractional cycle
† Fixed initial condition
## TABLE D. 16
REACTOR-CYCLE RESULTS FOR STRATEGY 3 IN CASE III
(48 Month Horizon, 0% P.V. Rate, Reference Nuclear Unit Costs, No Shape Constraints)

<table>
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<th>Average Cycle Energy Cost ($/MWH)</th>
<th>Incremental Cycle Energy Cost ($/MWH)</th>
<th>Reload Enrichment (w/o U-235)</th>
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* Fractional cycle  
† Fixed initial condition  
** Short-notice enrichment change (5.0 w/o U-235 was upper limit permitted by QKCORE).
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<tr>
<th>Reactor-Cycle</th>
<th>Cycle Length (Months on-line)</th>
<th>Cycle Energy (GWH)</th>
<th>Average Cycle Energy Cost ($/MWH)</th>
<th>Incremental Cycle Energy Cost ($/MWH)</th>
<th>reload Enrichment (w/o U-235)</th>
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* Fractional cycle
† Fixed initial condition
** 1.5 w/o U-235 was lower limit permitted by QKCORE.
# TABLE D. 18
REACTOR-CYCLE RESULTS FOR STRATEGY 2 IN CASE IV
(48 Month Horizon, 12% P.V. Rate, Reference Nuclear Unit Costs, No Shape Constraints)

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<th>Incremental Cycle Energy Cost ($/MWh)</th>
<th>Reload Enrichment (w/o U-235)</th>
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* Fractional cycle  
† Fixed initial condition
### TABLE D. 19
**REACTOR-CYCLE RESULTS FOR STRATEGY 3 IN CASE IV**

(48 Month Horizon, 12% P.V. Rate, Reference Nuclear Unit Costs, No Shape Constraints)

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<th>Average Cycle Energy Cost ($/MWH)</th>
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* Fractional cycle  
† Fixed initial condition  
** Short-notice enrichment change (5.0 w/o U-235 was upper limit permitted by QKCORE).
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* Fractional cycle
† Fixed initial condition
** 1.5 w/o U-235 was lower limit permitted by QKCORE.
# TABLE D. 21

## REACTOR-CYCLE RESULTS FOR STRATEGY 2 IN CASE V

(48 Month Horizon, 7% P.V. Rate, Low Nuclear Unit Costs, No Shape Constraints)

<table>
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<tr>
<th>Reactor-Cycle</th>
<th>Cycle Length (Months on-line)</th>
<th>Cycle Energy (GWH)</th>
<th>Average Cycle Energy Cost ($/MWH)</th>
<th>Incremental Cycle Energy Cost ($/MWH)</th>
<th>Reload Enrichment (w/o U-235)</th>
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* Fractional cycle
† Fixed Initial condition
TABLE D. 22
REACTOR-CYCLE RESULTS FOR STRATEGY 3 IN CASE V
(48 Month Horizon, 7% P.V. Rate,
Low Nuclear Unit Costs, No Shape Constraints)

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<th>Reactor-Cycle</th>
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<th>Incremental Cycle Energy Cost ($/MWH)</th>
<th>Reload Enrichment (w/o U-235)</th>
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* Fractional cycle  
† Fixed initial condition  
** Short-notice enrichment change (5.0 w/o U-235 was upper limit permitted by QKCORE).
TABLE D. 23
REACTOR-CYCLE RESULTS FOR STRATEGY 1 IN CASE VI
(48 Month Horizon, 7% P.V. Rate,
High Nuclear Unit Costs, No Shape Constraints)

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* Fractional cycle
† Fixed initial condition
** 1.5 w/o U-235 was lower limit permitted by QKCORE
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* Fractional cycle
† Fixed initial condition
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* Fractional cycle  
† Fixed initial condition  
** Short-notice enrichment change (5.0 w/o U-235 was upper limit permitted by QKCORE)
### TABLE D. 26

**REACTOR-CYCLE RESULTS FOR STRATEGY 1 IN CASE I AT END OF FIRST SHAPE ITERATION**

(72 Month Horizon, 7% P.V. Rate, Reference Nuclear Unit Costs, No Shape Constraints)

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* Fractional cycle
† Fixed initial condition
** 1.5 w/o U-235 was lower limit permitted by QKCORE
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* Fractional cycle
† Fixed initial condition
### Table D.28

**Reactor-Recycle Results for Strategy 3 in Case I at End of First Shape Iteration**

(72 Month Horizon, 7% P.V. Rate, Reference Nuclear Unit Costs, No Shape Constraints)

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<td>14</td>
<td>7060</td>
<td>2.006</td>
<td>1.853</td>
<td>4.088</td>
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<td>1.630</td>
<td>4.001</td>
</tr>
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<td>1.978</td>
<td>1.196</td>
<td>3.543</td>
</tr>
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<td>1.866</td>
<td>1.160</td>
<td>3.490</td>
</tr>
<tr>
<td>B-1</td>
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<td>710</td>
<td>1.735</td>
<td>0.814</td>
<td>-</td>
</tr>
<tr>
<td>B-2</td>
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<td>7260</td>
<td>1.820</td>
<td>1.397</td>
<td>3.715**</td>
</tr>
<tr>
<td>B-3</td>
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<td>1.911</td>
<td>1.853</td>
<td>4.105</td>
</tr>
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<td>B-4</td>
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<td>7305</td>
<td>1.820</td>
<td>1.101</td>
<td>3.502</td>
</tr>
<tr>
<td>B-5</td>
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<td>3.574</td>
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<td>B-6</td>
<td>12</td>
<td>7267</td>
<td>1.839</td>
<td>1.160</td>
<td>3.635</td>
</tr>
<tr>
<td>C-1</td>
<td>10†</td>
<td>6580</td>
<td>1.803</td>
<td>1.322</td>
<td>3.6†</td>
</tr>
<tr>
<td>C-2</td>
<td>14</td>
<td>7580</td>
<td>1.961</td>
<td>1.853</td>
<td>4.074</td>
</tr>
<tr>
<td>C-3</td>
<td>15</td>
<td>7960</td>
<td>1.993</td>
<td>1.849</td>
<td>4.217</td>
</tr>
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<td>C-4</td>
<td>12</td>
<td>7320</td>
<td>1.877</td>
<td>1.101</td>
<td>3.528</td>
</tr>
<tr>
<td>C-5</td>
<td>12</td>
<td>7040</td>
<td>1.892</td>
<td>1.160</td>
<td>3.464</td>
</tr>
<tr>
<td>D-1</td>
<td>3*</td>
<td>2057</td>
<td>1.487</td>
<td>1.008</td>
<td>-</td>
</tr>
<tr>
<td>D-2</td>
<td>15</td>
<td>8373</td>
<td>2.032</td>
<td>1.537</td>
<td>5.0**</td>
</tr>
<tr>
<td>D-3</td>
<td>12</td>
<td>7885</td>
<td>1.874</td>
<td>1.849</td>
<td>4.191</td>
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<tr>
<td>D-4</td>
<td>12</td>
<td>8200</td>
<td>1.763</td>
<td>1.099</td>
<td>3.563</td>
</tr>
<tr>
<td>D-5</td>
<td>12</td>
<td>7540</td>
<td>1.813</td>
<td>1.101</td>
<td>3.564</td>
</tr>
<tr>
<td>D-6</td>
<td>11</td>
<td>7225</td>
<td>1.808</td>
<td>1.134</td>
<td>3.616</td>
</tr>
<tr>
<td>E-1</td>
<td>17</td>
<td>8391</td>
<td>2.144</td>
<td>1.399</td>
<td>3.2†</td>
</tr>
<tr>
<td>E-2</td>
<td>13</td>
<td>6960</td>
<td>1.964</td>
<td>1.851</td>
<td>4.168</td>
</tr>
<tr>
<td>E-3</td>
<td>12</td>
<td>6980</td>
<td>1.843</td>
<td>1.101</td>
<td>3.485</td>
</tr>
<tr>
<td>E-4</td>
<td>15</td>
<td>7519</td>
<td>1.897</td>
<td>1.170</td>
<td>3.504</td>
</tr>
<tr>
<td>F-1</td>
<td>16</td>
<td>8712</td>
<td>2.081</td>
<td>0.436</td>
<td>3.2†</td>
</tr>
<tr>
<td>F-2</td>
<td>14</td>
<td>8082</td>
<td>2.043</td>
<td>1.160</td>
<td>5.0</td>
</tr>
</tbody>
</table>

* Fractional cycle  
† Fixed initial condition  
** Short-notice enrichment change (5.0 w/o U-235 was upper limit permitted by QKCORE).
E.1 SYSINT Discussion

E.1.1 Introduction

SYSINT is a computerized version of the **SYSTEM INTEGRATION MODEL** (SIM) discussed in Chapter 3. A summary of SYSINT characteristics was presented in Section 3.6.

SYSINT performs (1) the Booth-Baleriaux probabilistic utility system simulation for each time period in the planning horizon, (2) estimates all of the required cost components and, (3) outputs data for SYSOPT, the computerized **SYSTEM OPTIMIZATION MODEL** (SOM) of Chapter 4 and Appendix F.

E.1.2 Code Structure and Mode of Operation

Table E.1 presents a summary of SYSINT subroutine information while Figure E.1 portrays the general sequence of operations occurring in a SYSINT production run. (Table E.2 presents information relative to possible error messages printed by subroutine ERRMSG.)

The input to SYSINT is modularized into three separate datasets to permit maximum flexibility in changing parameters with a minimum number of input cards: strategy data (alternative maintenance schedules) change often, period data (e.g., load forecasts and fossil fuel costs) less often, unit data (heat rates) seldom.
### Table E.1

#### Summary of SYSINT Subroutines

<table>
<thead>
<tr>
<th>Name</th>
<th>Called By</th>
<th>Calls</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>SYSINT (Main)</td>
<td>-----</td>
<td>SUPSIM, STRTIM</td>
<td>Main Program</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Prints Title</td>
</tr>
<tr>
<td>BLOCK DATA</td>
<td>-----</td>
<td>-----</td>
<td>Initializes data in COMMON areas</td>
</tr>
<tr>
<td>SUPSIM (QUIT)</td>
<td>SYSINT</td>
<td>BASIC, PERIOD, STRATG, PRESIM, PUNCHR, ERRMSG, CMPTIM, ERASE</td>
<td>Supervises entire SYSINT simulation; Reads Control cards; Has ENTRY QUIT to terminate execution if severe error occurs.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SUPSIM</td>
<td>PRPNDX</td>
</tr>
<tr>
<td></td>
<td></td>
<td>INNDEX</td>
<td>Reads basic system information (unit data)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ERMMSG</td>
<td></td>
</tr>
<tr>
<td>PERIOD</td>
<td>SUPSIM</td>
<td>INNDEX, ERMMSG</td>
<td>Reads period data and stores it on direct access device</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INNDEX (PRPNDX)</td>
<td>BASIC, PERIOD, STRATG, LDGORD, COMPRS</td>
<td>ERMMSG, ERASE</td>
<td>Determines INDEX corresponding to a particular IDNO; Has ENTRY PRPNDX to initialize procedure.</td>
</tr>
<tr>
<td>Name</td>
<td>Called By</td>
<td>Calls</td>
<td>Purpose</td>
</tr>
<tr>
<td>--------</td>
<td>-----------</td>
<td>------------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>STRATG</td>
<td>SUPSIM</td>
<td>INNDEX ERRMSG ERASE</td>
<td>Reads refueling and maintenance strategy input</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRESIM</td>
<td>SUPSIM</td>
<td>NUSCAL LDGORD SYSGEN GWHNRG PUNCHR CMPTIM ERASE</td>
<td>Performs pre-simulation data manipulation for each period</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NUSCAL</td>
<td>PRESIM</td>
<td>GWHNRG ERRMSG</td>
<td>Changes spacing of PROB from that determined by input PKMW to DM</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDGORD</td>
<td>PRESIM</td>
<td>INNDEX COMPRS RETMRG MERGER ERRMSG ERASE</td>
<td>Optimizes loading order according to NORDOP and encodes order as 1000*NPT + INDEX</td>
</tr>
</tbody>
</table>
Table E.1--Continued

<table>
<thead>
<tr>
<th>Name</th>
<th>Called By</th>
<th>Calls</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPRS (RETMRG)</td>
<td>LDGORD</td>
<td>INNDEX</td>
<td>Performs STATUS vs. IDNO check and then compresses and transfers NORDER into NTEMP; Alter incremental cost curves and optimizes startup order; Has ENTRY RETMRG to return incremental cost curves to original values.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ERRMSG</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ERASE</td>
<td></td>
</tr>
<tr>
<td>MERGER</td>
<td>LDGORD</td>
<td>ERRMSG</td>
<td>Merges newly started plant increments with those of previously started plants</td>
</tr>
<tr>
<td>SYSGEN</td>
<td>PRESIM</td>
<td>SUBPLT</td>
<td>Supervises actual simulation;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GWHNRG</td>
<td>Calculates costs, etc.;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ADDPLT</td>
<td>Prints period output.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PROBX</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SUSDNO</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>PUNCHR</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ERRMSG</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ERASE</td>
<td></td>
</tr>
<tr>
<td>SUBPLT</td>
<td>SYSGEN</td>
<td>ERRMSG</td>
<td>Subtracts outages of plant-of interest from PROB</td>
</tr>
<tr>
<td>GWHNRG</td>
<td>PRESIM</td>
<td>NUSCAL</td>
<td>Calculates energy under section of PROB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SYSGEN</td>
<td></td>
</tr>
</tbody>
</table>
Table E.1--Continued

<table>
<thead>
<tr>
<th>Name</th>
<th>Called By</th>
<th>Calls</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADDPLT</td>
<td>SYSGEN</td>
<td>ERRMSG</td>
<td>Adds outages of plant-of-interest into PROB</td>
</tr>
<tr>
<td>PROBX</td>
<td>SYSGEN</td>
<td>------</td>
<td>Linearly interpolates PROB at a particular equivalent load</td>
</tr>
<tr>
<td>SUSDNO</td>
<td>SYSGEN</td>
<td>------</td>
<td>Estimates number of startup-shutdowns during the period</td>
</tr>
<tr>
<td>PUNCHR</td>
<td>SUPSIM</td>
<td>ERRMSG DAYTIM WHEN*</td>
<td>Performs output operations for SYSINT-to-SYSOPT output;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dependent upon IBM Data Utility Program IEBUPDTE (Release 20) (3)</td>
</tr>
<tr>
<td>ERRMSG</td>
<td>SUPSIM</td>
<td>QUIT</td>
<td>Prints error messages;</td>
</tr>
<tr>
<td></td>
<td>BASIC</td>
<td></td>
<td>Chooses to terminate execution if severe error occurs (see Table E.2)</td>
</tr>
<tr>
<td></td>
<td>PERIOD</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>INNDEX</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>STRATG</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NUSCAL</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LDGORD</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>COMPRS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MERGER</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SYSGEN</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SUBPLT</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ADDPLT</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PUNCHR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>Called By</td>
<td>Calls</td>
<td>Purpose</td>
</tr>
<tr>
<td>------------</td>
<td>-----------</td>
<td>----------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>CMPTIM</td>
<td>SYSINT</td>
<td>WHEN*</td>
<td>Calls MIT internal clock routines to monitor execution time;</td>
</tr>
<tr>
<td>(STRTIM)</td>
<td>SUPSIM</td>
<td>TIMING*</td>
<td>Prints subroutine-to-subroutine transfer times;</td>
</tr>
<tr>
<td>(DAYTIM)</td>
<td>PRESIM</td>
<td></td>
<td>Has ENTRY STRTIM to start clock and ENTRY DAYTIM to print calendar date and time.</td>
</tr>
<tr>
<td></td>
<td>PUNCHR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ERASE</td>
<td>SUPSIM</td>
<td>______</td>
<td>MIT Assembler Language program that sets arrays to zeroes rapidly</td>
</tr>
<tr>
<td></td>
<td>PRPNDX</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>STRATG</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PRESIM</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LDGORD</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>COMPRS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SYSGEN</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*WHEN and TIMING ARE MIT internal clock subroutines
Figure E.1

SYSINT Flowchart

START

SYSINT (MAIN)

SUBROUTINE

SUPSIM

CONTROL CARD

"START"

BASIC

"SAVE"

PERIOD

"STRATEGY"

STRATG

"COMPUTE"

DO N = 1, NPER

NEXT SET OF UNIT DATA

NEXT STRATEGY

PRESIM, SYSGEN, ETC.: BOOTH-HALARIA PROBABILISTIC UTILITY SIMULATION
FOR PERIOD N

IF "STRATEGY"

IF "SAVE"

IF "START"

IF "STOP"

"OUTPUT TAPE"

"OUTPUT CARD"

SYSINT-TO-SYSOPT OUTPUT

IF PUNCH STEP: IBM DATA HANDLING UTILITY IERPITCH

IF STORE STEP: IBM DATA HANDLING UTILITY IERPUPDATE

CARD FORMAT

DISK FORMAT

STOP
Table E.2  
SYSINT Error Messages Printed by ERRMSG

<table>
<thead>
<tr>
<th>Number*</th>
<th>Source</th>
<th>Action after Printing</th>
<th>Error</th>
<th>Error Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NUSCAL</td>
<td>CALL QUIT</td>
<td>PROB</td>
<td>PROB not dimensioned large enough</td>
</tr>
<tr>
<td>2</td>
<td>SUBPLT</td>
<td>CALL QUIT</td>
<td>Capacity of unit greater than minimum load</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ADDPLT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>NUSCAL</td>
<td>RETURN</td>
<td>Warning of large error in changing PROB spacing</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>NUSCAL</td>
<td>CALL QUIT</td>
<td>New PROB violate properties of probability function</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>SYSGEN</td>
<td>RETURN</td>
<td>Warning of large error in total area under PROB</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>SUPSIM</td>
<td>CALL QUIT</td>
<td>Input deck has improper sequence &amp;/or card</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BASIC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PERIOD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>STRATG</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>INNDEX</td>
<td>CALL QUIT</td>
<td>Invalid or inconsistent IDNO encountered</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>SUPSIM</td>
<td>STOP</td>
<td>&quot;STOP&quot; Control Card; many small errors; etc.</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>LDGORD</td>
<td>CALL QUIT</td>
<td>Input NORDER is improper</td>
<td></td>
</tr>
<tr>
<td></td>
<td>COMPRS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MERGER</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PUNCHR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A (=10)</td>
<td>QUIT</td>
<td>STOP</td>
<td>QUIT executed &quot;RETURN&quot; to ERRMSG</td>
<td></td>
</tr>
<tr>
<td>B (=11)</td>
<td>PUNCHR</td>
<td>RETURN</td>
<td>Nuclear upper increments not consecutive</td>
<td></td>
</tr>
<tr>
<td>C (=12)</td>
<td>PUNCHR</td>
<td>RETURN</td>
<td>Nuclear minimums not base-loaded</td>
<td></td>
</tr>
</tbody>
</table>

*The error number initiating the ERRMSG print appears as the rightmost digit in the accumulated ERRCOD which is printed as part of the message.
E.1.3 SYSINT-to-SYSOPT Output Data Transfer

SYSINT-to-SYSOPT output can be obtained in either disk, magnetic tape or punched card format. All are in card image form with LRECL=80. Table E.3 summarizes the control cards and output modes.

Figure E.2 portrays accumulation of SYSINT strategy output during a single CALC step (see Section E.3, Figure E.5) in the computer run. After terminating the CALC step, the output must be separated by a STORE step or by hand for input into SYSOPT. As an example of the volume of output data involved, each of the three strategies of Chapter 5 (72 time periods each) produced 2164 punched cards. Figure E.3 presents the punched output of the sample SYSINT run shown in Figure E.5 of Section E.3.

Each strategy output deck begins with "./ADD NAME=" and "---BEGIN" cards and ends with a "---ABORT" or "---END" card followed by two blank cards. The ADD NAME card is used as input to the IBM utility IEBUPDTE (3) in the STORE step. [The IBM utility IEBPTPCH, used for printing and/or punching datasets in the PUNCH step, is also detailed in (3).] The ABORT card signifies abnormal termination of SYSINT-to-SYSOPT output due to SYSINT execution errors. The END card signifies normal (successful) completion of all SYSINT calculations and output.
# Table E.3

**SYSINT-to-SYSOPT Output Modes**

<table>
<thead>
<tr>
<th>Mode</th>
<th>&quot;OUTPUT&quot; Control</th>
<th>PUNCH Step Result (if included)</th>
<th>STORE Step Result (if included)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>&quot;NO TAPE&quot;</td>
<td>•••••</td>
<td>•••••</td>
<td>No SYSINT-to-SYSOPT output</td>
</tr>
<tr>
<td>II</td>
<td>&quot;CARD&quot;</td>
<td>•••••</td>
<td>•••••</td>
<td>Punched Cards only</td>
</tr>
<tr>
<td>III</td>
<td>&quot;TAPE&quot;</td>
<td>Card Output</td>
<td>Disk Output</td>
<td>Most Versatile</td>
</tr>
</tbody>
</table>

**Notes:**

1. **Card Output:**
   - (a) No limit on number of strategies in one SYSINT run.
   - (b) May be put through later STORE step to create Disk output.
   - (c) Strategies may be separated and input directly into SYSOPT.

2. **Tape Output:**
   - (a) May be temporary direct access dataset on SYSDA device if STORE step used immediately to create Disk output with no limit on number of strategies per run.
   - (b) If actually a (backup) tape, may be put through later STORE step to create Disk output with no limit on number of strategies per run.
   - (c) May be input directly into SYSOPT but limit of one strategy per SYSINT run (i.e., per tape file).

3. **Disk output:** Preferred SYSOPT input since Disk output is on-line, provides faster data transfer and does not idly tie up tape drive during subsequent SYSOPT execution.
Figure E.2

SYSINT - to - SYSOPT Output Data Transfer

SYSINT

ORDER OF CALCULATION

"S" FOR STRATEGY

SINGLE TAPE FILE OR SINGLE PUNCHED CARD DECK

"STORE" JOB STEP

MANUALLY SEPARATED

S-1

S-2

S-3

OR

OR

SYSOPT
-459Figure EA3
-Example of SYSINT-to-SYSOPT Output Data
----TI

FfCIeN -,T-ATI'I,, f A11- -A -11-11 OUOU%,'')N

~

Am'~

S3"3 v1 100
,40-

k S MAI'4IT.UATA

Sr

IN

o~ tI% .- I.

?'/14/73 At

c*c

*'9..pi

l*31*4,9.O3 -- ---- --f * AAM0e.)tS

I T P40U

0
t J~o

-. " illS

I VALIJE1)

IT'. "L'IMh) WU Fa)LLw noI4ULAlILD
/ 73
13'
0.......
EXAMPLE *4 ),
: I-,.IHAH
It IIi r( 4JOEI (
w!19' ViJ4CLDO0UTA(,ES I
11 loOnooUd 710*0900
14-0030
'414
700
14i PJCh
1
3730h..t*'733
10 73p.b36~77. 314hle 3791
.1 0 e'7.000o 6?0.*2000
4AX
3400
a
d.Sb?.?624. " ?.lI7127*40
* 3b34ShV7ep3ba.25..

4

7b?. 335031 .43

83?"0'

-AfT

0O0,4MlnNLN=
eV00*MwWE(AK=
3b00HwNRGhZ
'i.$LOFLx 0.13Ib47Oj0
*FXPDEM=
948*9v9'9999'c9999
9X%~*4g37S
K~jEN= 8.?3.34?44bb286O4V6 .IDJ'41=
4N5N* ?;47.5413'.1731%?66
WcXPt'44=
30,111193h4Z4423b9
*II.J'4?=
'14S4V~m
3'eJi31I4',!.44?33W
9P0ol =
?600394.?41810I5
0 ICU04JZ
4
S 4dK akoz 1eI304o..),)'4F40J
9 %NNPP(()=
I14459of4407$8i$
910L 4=
%US'A= 20'Jo554841 Os100 lb1 NK v:3 0.42o10199de9448OJ-3,1C4Sz
SNNStJSm
206.5c-409a37 0 14033d
9sSniIJT= 2hoobo)8.8'2761999
.IL)J~b
SNKTOTz
IeI3'.4.53197403
'va4aT0Tz
l1,47'*h.3i8964Sv7
9I0J'47Z
E4'-It= 301lj1.Y3b42'e?3SV
91OFALS=
2Yj1.dI63

kO~NSDN
EXP'ENz

:STRTU

AVLHTY

ENERGY

E~phja.

ExPCW

EAP04TU

3? 199
?069

O*
0.

0.
09
09
0'

0.

LOST

19.0000 90-0090
0.0
6 7.-poo
146.38.7b
3b55e
i3399.
38.0000 Bb.000§
0.0
e209.'oo
474.961I71
5070586.
yl2?o6.
"00006096.0 TU4 IAEioo TO F-JLLOw 51'4ULATEO
?/3MA/73
1*39*59.01 .............
EX404PLE NO.
5
: MUJLTIPLE INCftmLNT HOIJTH-9ALEI41AUA 140DEL (V-2*TNEN 111-2)
3 10@00000 71000600
1000000
%41~4
600
A
7.655oo?3?06Oc2000867)0.1302.7153
.?575032

&

0

65700000

6?G.5000

* 380375048
'FNLYCT
4v1%ISTX
?00Q0,UOrNLN=
e000.lMWPfA9z
3$00wMW#4RGh*
'4wSP1Nu
A0vvLOFLz 0.3'j0470J0
,EAPOE~dz 948.9V9-#999999999
EXPGVE~s 418.88063S5763
*X.4e"LEN=
6S3.9d046346be0502
9 1UaJ143=
KNNGE4K
264.84'ilbW4$9ebl
*F~tL"W=
3001111I93b4242339
*IDJ4?=
'JNs-'VD.
30*1111936424?331e
904'u~= 2481090,4h3857021
91cum'3=
SNKPR40

SUSD31z

1a276012.-ad2SIS141

10669.AD4PZ250419t

SNNSLJSZ

SN4KTOTZ

EIN'~=

10664.882?S041VO

127601?.'36PS51~41
301111.93b4a.?3'i

CST'RTU
AVLRTI
19.0000 90.000"
18.0000 H,00004

FEEGY
0.0
0.0

9
4,-W4 ?=0SO7.$dl3418$~
*1UJ44=
*)KU
.3b3797A9070917l30-Il*1OU45=
9ISiT0T=
249Ib.35?080ob8
qjaJJ46z

94T,)T=
1?15727.7695669e?
,TcTALtz
e74?97?.?'.4'5SOJ0.
EAPFM'..
f: 1.,o 'J0
6i0q,30O

*IOj'47=

200.
0.

0.
o.
0.
0.
09

0.

Et P60P4
6.54's33

EAPHTU
COST
lt7363.
)47199.
4M4.39331
5100106.
4L94
...
000000004TH PERI1OD TC F LluO S114ULATED
?/10/#73
10149b5.01..............
EXAMPLE 40.
6' : POLTWPLE PC.t'mENT OOOTH-9'ALL41AUA MODFL filI-.'.THFN V-?)
4
10o.0000
730.0000
14.00U0
'41'4
800
13
1.iS1031?jeO64i

18866,096500

.285'175032

0
0
3300
.360375048
06FNLTCjT
'4*14ST*

'4AX

657.0600
II

6?0.3000

7.6.)103,31..oo.44oo-.,

~5l.3.b5e.?O0

?00,'Mwf0LNx
e,)00,mwPFA.=
UaO.N94Hm6*.z
tASONx-200U0000000.PLOFL2 0.1>047330
#FAPflEmz
948.9'#9149949999
#AN6LEN
6-,3.90396306600b301
*lOUN1Z
EJ.I'ENx *18.880635757a3
XNNGFNz
24.84100,699S23
9FAwE'4w=
3o.ljI193b'Q423b4
.!L)JN2z
It4%S4V0.
ju.I111Q3b424?33*
#v4lUA.
?%6hIh.~a9291I1l
9IOU43=
SNK-W0.
93~746~
*~N""Ojqr)
JOS057.$11348d5
*JUJ'14=
.bNw*_U~z Q.3b379740?09I?33U-.!O'J'4S,
106f.bM422504196
SUSD~=
SNNSUSS
9M'25'3,
SNKTOTS
I
?C.79lf,
Eo4*z
30311.93b4242364.

94.SOTUTZ
.N.OT=
j,~?.b'697
,IOTAL*=
e7'qjjOv7.9d3%#4789~

CSVITU
AVLOJY
EULOG1(Y
f AI-H*'
EAP*'WH
19 7.0 '.q9
0.0
6 7.'§a0
19.0000 40-000l
16.0000 'I5.0000
0.0
0.':0a
45. MP3464.
-------E4
OF !).lpATUrY alit A34F=10O00n0? (0N ?/ I "/

1AJ~04S
,~~=

LAPITL,

230?400.

40194I9Oi.862
. AT1

200.
0.

09
0'
0.
0.

b

UI046=
09

COS.T

]'aq4sb.

1*14,9.01----------

0.

37'.1i503


E.1.4 Altering Dataset Reference Numbers

Table E.4 presents the dataset reference number for each input/output device, their meaning and instructions for altering them for other computer installations.
<table>
<thead>
<tr>
<th>Fortran Symbol</th>
<th>Meaning</th>
<th>Current Value</th>
<th>Instructions for Altering</th>
</tr>
</thead>
<tbody>
<tr>
<td>RD</td>
<td>Card Reader</td>
<td>5</td>
<td>See BLOCK DATA subroutine</td>
</tr>
<tr>
<td>WT</td>
<td>Output Printer</td>
<td>6</td>
<td>See BLOCK DATA subroutine</td>
</tr>
<tr>
<td>CARD</td>
<td>Card Punch</td>
<td>7</td>
<td>See BLOCK DATA subroutine</td>
</tr>
<tr>
<td>TAPE</td>
<td>Output tape or disk for SYSINT-to-SYSOPT output</td>
<td>8</td>
<td>See BLOCK DATA subroutine and any //G.FT08F001 Data Definition cards (see Section E.3)</td>
</tr>
<tr>
<td></td>
<td>Temporary direct access device storing period-by-period forecasts</td>
<td>9</td>
<td>See PERIOD and PRESIM subroutines and any //G.FT09F001 Data Definition cards (see Section E.3)</td>
</tr>
<tr>
<td></td>
<td>Final Disk dataset</td>
<td>SYSUTZ</td>
<td>See Section E.3, Figure E.5</td>
</tr>
</tbody>
</table>
E.2 SYSINT Input Specifications

Table E.5 presents complete input specifications for SYSINT. The "START" Card 1 heads the plant data input module (Cards 2-10). The "SAVE" Card 11 heads the period data input module (Cards 12-20). Likewise, the "STRATEGY" Card 21 heads the maintenance strategy input module (Cards 22-24). "Compute" Cards 25-26 determine which periods of the strategy are executed. If no other modules are to be input and/or executed, a "STOP" Card 27 terminates SYSINT calculations.
Table E.5

**SYSINT Input Specifications**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Card 1</td>
<td>1-5</td>
<td>...</td>
<td>&quot;START&quot; Control card initiates input processing for plant data, normalized startup-shutdown frequency function and load-duration shapes</td>
</tr>
<tr>
<td>Card 2</td>
<td>1-10</td>
<td>...</td>
<td>&quot;PLANT DATA&quot; Header card for plant data</td>
</tr>
<tr>
<td>Card 3</td>
<td>1-5</td>
<td>I5</td>
<td>Number of units (stations) to be read in, 1 ≤ NOSTNS ≤ 100</td>
</tr>
<tr>
<td>Note:</td>
<td></td>
<td></td>
<td>For each of NOSTNS, a Card 4 of unit data is read in.</td>
</tr>
<tr>
<td>Card 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IDNO</td>
<td>1-4</td>
<td>I4</td>
<td>Unique unit identification number</td>
</tr>
<tr>
<td>NAME</td>
<td>5-8</td>
<td>A4</td>
<td>Unit name</td>
</tr>
<tr>
<td>TYPE</td>
<td>10</td>
<td>I,X,A1</td>
<td>Type of Unit:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>F= Fossil</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>H= Hydro (not currently used)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>N= Nuclear</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>P= Peaking</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>S= Pumped-storage (not currently used)</td>
</tr>
<tr>
<td>SUSDHT</td>
<td>11-20</td>
<td>F10.0</td>
<td>$Q_r$ unit startup-shutdown equivalent heat requirement, MegaBTU</td>
</tr>
<tr>
<td>PNOM</td>
<td>21-29</td>
<td>F9.5</td>
<td>$p_r$ unit performance probability, fraction</td>
</tr>
<tr>
<td>NPTS</td>
<td>30</td>
<td>I1</td>
<td>I total number of capacity increments, 1 ≤ I ≤ 5</td>
</tr>
<tr>
<td>Variable</td>
<td>Columns</td>
<td>Format</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>---------</td>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>MWPT</td>
<td>...</td>
<td>I4</td>
<td>$K_{ri}$ cumulative unit capacity, MW</td>
</tr>
<tr>
<td>HTRAT</td>
<td>...</td>
<td>F6.0</td>
<td>$h_{inc_{ri}}$ incremental heat rate, BTU/kwhe</td>
</tr>
</tbody>
</table>

**Note:** Continue (MWPT, HTRAT) sets until all I increments have been read in.

**Card 5**

... 1-20 ...

"NORMALIZED SUSD DATA" Header card for normalized startup-shutdown frequency function

**Note:** There are three Card 6's required to read in the 20 $\Omega$ values

**Card 6**

F(1) to F(20) 1-80 8F10.4 $\Omega(L'_{rl})$ normalized startup-shutdown frequency function at increments of 0.05 of $L'_{rl}$ ($0.05 \leq L'_{rl} \leq 1.00$); $\Omega(0)$ $\equiv 0$; linear interpolation between points; per day

**Card 7**

... 1-10 ...

"LOAD TYPES" Header card for load-duration shapes

**Card 8**

LDTYPS 1-5 I5 Total number of normalized load-duration shapes, $1 \leq LDTYPS \leq 25$

**Note:** For each of LDTYPS, Cards 9 and 10 of load shape data are read in.

**Card 9**

LDTYP 1-5 I5 Unique load-duration shape identification number, $1 \leq LDTYP \leq 25$
Variable | Columns | Format | Description
---|---|---|---
NUMONE | 6-10 | I5 | Number of l.'s to be prefixed to load shape data on Card 10, $0 \leq \text{NUMONE} \leq 49$

Note: There are $\{(50-\text{NUMONE} + 7)/8\}$ Card 10's to be read in for this LDTYPE

Card 10

| PROB | 1-80 | 8F10.4 | F completely normalized customer load-duration curve from minimum load to peak demand where $F_D = 0$ for first time. (Usually $F_D = 0$ at PROB (50) resulting in spacing of 2% of PKMW.), fractional duration

Card 11

| | 1-4 | | "SAVE" Control card signifying previous data on Cards 1-10 to be saved.

Card 12

| | 1-7 | | "OUTPUT", Control card for large volume of data to be transferred to SYSOPT

| | 8-11 | | "TAPE", SYSINT data output to temporary dataset with Dataset Reference Number = TAPE (See BLOCK DATA subroutine and Section E.1.3)

| | 8-11 | | "CARD", SYSINT data output to card punch with Dataset Reference Number = CARD (See BLOCK DATA Subroutine and Section E.1.3)

| | 8-14 | | "NO TAPE", SYSINT-to-SYSOPT data not desired

Note: Choose one or include all three types of Card 12 with only last one read being valid
<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Card 13</td>
<td>...</td>
<td>1-14</td>
<td>&quot;OUTPUT PRINT &quot;Control card for printed output on Data-set Reference Number = WT (See BLOCK DATA Subroutine and Section E.1.4)</td>
</tr>
<tr>
<td></td>
<td>...</td>
<td>15-18</td>
<td>&quot;MINI&quot; prints input edit, unit incremental costs, unit production totals and system totals</td>
</tr>
<tr>
<td></td>
<td>...</td>
<td>15-18</td>
<td>&quot;MIDI&quot; prints MINI plus Unit increment loading during load step of Booth-Baleriaux algorithm</td>
</tr>
<tr>
<td></td>
<td>...</td>
<td>15-18</td>
<td>&quot;MAXI&quot; prints MIDI plus all F's calculated at each convolve or deconvolve operation (Warning: This option should be used only for very small problems.)</td>
</tr>
</tbody>
</table>

**Note:** Choose one or include all three types of Card 13 with only last one read being valid.

**Note:** A set of Cards 14-20 is included for each of NPERS (up to 100) periods desired in planning horizon. Each NPER need not be entered in numerical order.

**Card 14**

| ...     | 1-6   | ... | "PERIOD" Header card |
|         | 7-10  | A4  | Free for Comments    |

**Card 15**

| PDTITL  | 1-80  | 10A8 | Period title         |

**Card 16**

<table>
<thead>
<tr>
<th>NPER</th>
<th>1-4</th>
<th>I4</th>
<th>Period number, $1 \leq \text{NPER} \leq 100$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDTYPE</td>
<td>5-8</td>
<td>I4</td>
<td>Load shape desired, $1 \leq \text{LDTYPE} \leq 25$</td>
</tr>
<tr>
<td>Variable</td>
<td>Columns</td>
<td>Format</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>---------</td>
<td>--------</td>
<td>-------------</td>
</tr>
</tbody>
</table>
| PKMW     | 9-16    | F8.0   | Peak customer demand, MW  
(The resulting minimum load  
must not be less than largest  
unit on the system.) |
| SPNRES   | 17-24   | F8.0   | Spinning reserve requirement,  
(Expressed) MW |
| DM       | 25-32   | F8.0   | Desired equivalent load curve  
spacing, should be 1 to 4% of  
PKMW if PROB (49) ≠ 0 (Card  
10), MW |
| DT       | 33-40   | F8.0   | T', Duration of period, hours |
| CSTEMR   | 41-48   | F8.0   | \(\bar{\epsilon}_U\), Average cost of  
emergency purchases, $/MWH |
| CSTFOS*  | 49-56   | F8.0   | \(\phi_F\), Cost of fossil fuel for  
all fossil units, $/\text{MegaBTU} |
| CSTNUK*  | 57-64   | F8.0   | \(\phi_N\), Cost of nuclear fuel for  
all nuclear units, $/\text{MegaBTU} |
| CSTPKG*  | 65-72   | F8.0   | Cost of fuel for all peaking  
units, $/\text{MegaBTU} |
| AVLALL*  | 73-80   | F8.0   | \(p_r\), Performance probability  
for all units, (If 0.0 or  
blank, 100*PNOM_r used for  
each unit for first period  
read.), per cent |

* Requires non-zero, non-negative entry to be effective.  
To input zero, use 1.E-50. If left blank, has no  
effect on data remaining after previous period was  
processed.

**Note:** Card 17 included for each unit whose data is to  
be altered from current values (i.e., last  
period processed plus effects of CSTFOS, CSTNUK,  
CSTPKG or AVLALL for this period).

**Card 17 (Optional)**

<table>
<thead>
<tr>
<th>...</th>
<th>1-5</th>
<th>...</th>
<th>&quot;ALTER&quot; Control Card</th>
</tr>
</thead>
</table>
| ID  | 17-20 | 11X,14 | IDNO for unit whose data is  
to be altered |
<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CST*</td>
<td>21-30</td>
<td>F10.4</td>
<td>$\phi$ unit fuel cost. $\phi$/MegaBTU</td>
</tr>
<tr>
<td>AVL*</td>
<td>31-40</td>
<td>F10.4</td>
<td>$p_r$ unit performance probability, per cent</td>
</tr>
<tr>
<td>ENER*</td>
<td>41-50</td>
<td>F10.4</td>
<td>Scarce-resource energy available (not currently used)</td>
</tr>
</tbody>
</table>

**Note:** Cards 18-20 optional if period is to use same startup-shutdown data remaining after previous period was processed.

**Card 18**

... 1-9 ...

"SUSD DATA" Control Card

**Card 19**

<table>
<thead>
<tr>
<th>NORDOP</th>
<th>1-5</th>
<th>I5</th>
<th>Loading order optimization option:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>=1, no optimization, NORDER used as input. Each of NOENTY represents next increment of that unit. (SPNRES, NOBASE and NOPEAK ignored).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>=2, Base group order as is; Intermediate group started in given order for either economic or spinning reserve reasons; Peaking group started in economic order after all of increments in Intermediate group.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>=3, Same as 2 but Intermediate group started in economic order</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>=4, Same as 3 but Peaking group competes economically after last unit of Intermediate group is started.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NOENTY</th>
<th>6-10</th>
<th>I5</th>
<th>Number of NORDER entries to be read</th>
</tr>
</thead>
</table>

| NOBASE | 11-15 | I5   | The first NOBASE entries in NORDER form the Base group of increment and are started in the order specified (i.e., the must-run increments) |
Variable | Columns | Format | Description
--- | --- | --- | ---
NOPEAK | 16-20 | I5 | The last NOPEAK entries in NORDER form the Peaking group regardless of unit TYPE. The Intermediate (central) group is made up of the remaining NOENTY-NOBASE-NOPEAK entries in NORDER.

Note: There are \([(NOENTY + 15)/16]\) Card 20's to be read in.

Card 20

NORDER (1) 1-80 | 16I5 | Input startup-shutdown order, unit (increment) IDNO. SYSINT automatically strips out off-line units and, therefore, it is wise to include all units in NORDER since various strategies will have different off-line units in the same period.

Note: A set of Cards 21-26 is included for each strategy (no limit on number of strategies) to be calculated.

Card 21

... 1-8 ... "STRATEGY" Control Card

Note: Card 13 required here if this is not first strategy.

Card 22

NPM 3 | 2X,L1 | Nuclear power management assumption check option, =F, SYSINT-SYSOPT assumptions concerning nuclear plant utilization not checked (That is, base-load nuclear minimums and all nuclear upper increments consecutive)

=T", Assumptions checked

IPLACE 4 | I1 | Version of strategy if same strategy was run previously
Variable | Columns | Format | Description
--- | --- | --- | ---
IDSTRG | 5-10 | I6 | Strategy identification number. If <0, skips SYSGEN calculations for input check

**Note:** SYSINT-to-SYSOPT output data stored using 8 alphabetic character membername = NPM + 10^6 *IPLACE + IDSTRG which should be unique to save old results with same IDSTRG

SGTITL | 11-80 | 10A7 | Strategy Title

**Card 23**

... | 1-11 | ... | "MAINT. DATA" Header card

**Note:** Card 24 must appear for each of NOSTNS.

**Card 24**

ID | 1-4 | I4 | Unit IDNO for which maintenance data card applies
NAM | 5-8 | A4 | Unit NAME (optional)
NOTZRO(1) | 11-15 | 2X,I5 | Unit installed just prior to period NOTZRO(1). If blank or zero, unit already installed before beginning strategy
NOTZRO(2) | 16-20 | I5 | Unit retired after period NOTZRO(2). If blank or zero, unit not retired during strategy
NDOWN(1) to NDOWN (20) | 21-80 | 20I3 | Period number during which unit off-line for maintenance (or refueling). If blank, zero or >NPERS has no effect

**Note:** If "COMPUTE" Card 25 omitted, only checks input of strategy and/or periods.

**Card 25**

... | 1-8 | ... | "COMPUTE "Control Card initiates computation of strategy for all indicated periods
... | 9-12 | ... | "SOME" (optional) only some of NPERS to be calculated
<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Note: Card 26 included only if &quot;SOME&quot; included on &quot;COMPUTE&quot; Card 25. Then, there must be ([(NPERS + 79)/80]) Card 26's.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Card 26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOPERD(1)</td>
<td>1-80</td>
<td>80L1</td>
<td>Calculate period NPER = Card Column? &quot;T&quot; = Yes &quot;F&quot; or blank = No</td>
</tr>
<tr>
<td>Note: Next card may be &quot;START&quot; Card 1, &quot;SAVE&quot; Card 11, &quot;STRATEGY&quot; Card 21 or &quot;STOP&quot; Card 27. Control reverts back to that point in Card input sequence.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Card 27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>1-4</td>
<td>...</td>
<td>&quot;STOP&quot; Control card to terminate SYSINT execution for this computer run.</td>
</tr>
</tbody>
</table>
E.3 SYSINT Sample Problems

Two sample problem input decks are presented in Figures E.4 and E.5. The deck in Figure E.4 was actually used to generate Reference Utility System Examples 1 and 2 (see Appendix C). The deck in Figure E.5 was likewise used for Examples 3 to 6 and to produce the SYSINT-to-SYSOPT output deck example in Figure E.3.
Figure E.4
SYSINT Sample Problem Input Deck I

```
// SYSTEM CLASSIFICATION : 101-100
// PLANT: 101
// MAIN LINE: 101
// CALC EXECUTION FILENAME: SAMPLE01
// CALC EXECUTION: TIME=1
// SUSD DATA
// LOAD TYPES
// 1 1 1 1
// 0.1 0.0 0.0 0.0
// 0.0 0.0 0.0 0.0
// 0.0 0.0 0.0 0.0
// SAVE
// OUTPUT NO TAPE
// OUTPUT PRINT: UNI
// PERIOD 1
// EXAMPLE NO. : DETERMINISTIC MODEL (NO FORCED-OUTAGES)
// 1 1 1000 0 10 19.96 10.48 10.35 10.00 100 90 100
// AVER: 30 15
// ALT: 70 50
// SUSD DATA
// P 1 2 3 4 1
// 505 303 404 202 101
// STRATEGY
// F1 1 SAMPLE SYSINT RUN PERFORMING CALCS. FOR EXAMPLES 1 & 2
// MAINT. DATA
// P 1 2 3 4 1
// 505 303 404 202 101
// COMPUTE SOWL
// IT
// START
// PLANT DATA
// 1 1 1 1 1
// 0.1 0.1 0.1 0.1 0.1
// 0.1 0.1 0.1 0.1 0.1
// 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
// SAVE
// OUTPUT NO TAPE
// OUTPUT PRINT: UNI
// PERIOD 1
// EXAMPLE NO. : DETERMINISTIC MODEL (REDUCED CAPACITIES)
// 1 1 1000 0 10 19.96 10.48 10.35 10.00 100 90 100
// AVER: 30 15
// ALT: 70 50
// SUSD DATA
// P 1 2 3 4 1
// 505 301 404 202 101
// STRATEGY
// F1 1 SAMPLE SYSINT RUN PERFORMING CALCS. FOR EXAMPLES 1 & 2
// MAINT. DATA
// P 1 2 3 4 1
// 505 301 404 202 101
// STOP
// ```
### Figure E.5

**SYSINT Sample Problem Input Deck II**

```plaintext
// Example 1
// MODEL 1
// ALPHE 300
// ALPHE 500
// SUSP DATA
// S 54 303 404 205 101
// PERIOD 2
// EXAMPLE NO. 2 : SINGLE INCREMENT HOUTH-MALLIAUX MODEL
// 1 1 509 9
// 2 1 100
// SUSP DATA
// S 54 303 404 205 101
// PERIOD 3
// EXAMPLE NO. 5 : MULTIPLE INCREMENT HOUTH-MALLIAUX MODEL
// 1 1 100
// 3 1 509 9
// SUSP DATA
// S 54 303 404 205 101
// PERIOD 4
// EXAMPLE NO. 6 : MULTIPLE INCREMENT HOUTH-MALLIAUX MODEL
// 4 1 100
// SUSP DATA
// S 54 303 404 205 101
// STRATEGY
// 71 2 SAMPLE SYSINT MIN HOUTH-MALLIAUX CALC. FOR EXAMPLES 3 THRU 5
// DATA
// 267
// 404
// 101
// 505
// 303
// COMP 508
// FFT
// STOP
```

### Table

<table>
<thead>
<tr>
<th>Period</th>
<th>Example No.</th>
<th>Model Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Mix-Model</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Single</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Single</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>Multiple</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>Multiple</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>Multiple</td>
</tr>
</tbody>
</table>

### Strategy

- Sample SYSINT MIN HOUTH-MALLIAUX CALC. FOR EXAMPLES 3 THRU 5
E.4 **SYSINT Source Listing**

The following is a Fortran IV source listing of the SYSINT code (included only in MIT library copies).
F.1 SYSOPT Discussion

F.1.1 Introduction

SYSOPT is a computerized version of the SYStem OPTimization Model (SOM) discussed in Chapter 4. A summary of SYSOPT characteristics was presented in Section 4.6.

SYSOPT performs the nuclear system optimization in conjunction with CORSOM's (specifically QKCORE of Appendix H using the Out-of-Kilter (O-O-K) Network Program of Appendix G. Input is accepted in the form of output from SYSINT (See Section E.1.3) as well as SYSOPT's own card input.

F.1.2 Code Structure and Mode of Operation

Table F.1 presents a summary of SYSOPT subroutines while Figure F.1 portrays the general sequence of operations occurring in a SYSOPT production run. (Table F.2 presents information relative to possible error messages printed by subroutine OPERR.)

In interfacing with the off-line code SYSINT, the SYSINT-to-SYSOPT output is transferred per Section E.1.3.

To be operational, SYSOPT must be link-edited with O-O-K since variables are transferred into and out of O-O-K's storage on-line by SYSOPT. The structure of the network itself and the resulting arc "Types" are indicated in Figure F.2.
### Table F.1
#### Summary of SYSOPT Subroutines

<table>
<thead>
<tr>
<th>Name</th>
<th>Called By</th>
<th>Calls</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>SYSOPT</td>
<td>--------</td>
<td>RDOPTN</td>
<td>Oversees entire SYSOPT optimization; Calls ICNPUT to permit INCORE Model to read input</td>
</tr>
<tr>
<td>(Main)</td>
<td></td>
<td>RDSTRG, RDPERS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ASMTYS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>WTPERS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SETUPN</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SETUPT</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CONVRG</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CHKSHP</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>EDTSHP</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>OPTMUM</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LOC</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>OPERR</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CMPTIM</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>STRTIM</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ICNPUT(^1)</td>
<td></td>
</tr>
<tr>
<td>BLOCK DATA</td>
<td>--------</td>
<td>---------------</td>
<td>Initialize data in Common areas; Dimensions Out-of-Kilter (O-O-K) Network Program arrays</td>
</tr>
<tr>
<td>RDOPTN</td>
<td>SYSOPT</td>
<td>PVINIT, OPERR</td>
<td>Reads in data directly pertinent to SYSOPT</td>
</tr>
</tbody>
</table>

\(^1\) INCORE Model subroutines (see QKCORE, Appendix H)
<table>
<thead>
<tr>
<th>Name</th>
<th>Called By</th>
<th>Calls</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDSTRG</td>
<td>SYSOPT</td>
<td>OPERR</td>
<td>Reads SYSINT-to-SYSOPT information relative to maintenance and refueling strategy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ERASE</td>
<td></td>
</tr>
<tr>
<td>RDPERS</td>
<td>SYSOPT</td>
<td>PDCALC</td>
<td>Reads SYSINT-to-SYSOPT information relative to period results</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OPERR</td>
<td></td>
</tr>
<tr>
<td>PDCALC</td>
<td>RDPERS</td>
<td>SUBPLT</td>
<td>Performs various pre-calculations for each period;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GWHNRG</td>
<td>Sets up some costs and limits for network arcs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PROBX</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>OPERR</td>
<td></td>
</tr>
<tr>
<td>SUBPLT</td>
<td>PDCALC</td>
<td>OPERR</td>
<td>Subtracts plant-of-interest from PROB; Similar to SUBPLT of SYSINT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GWHNRG</td>
<td>PDCALC</td>
<td>------</td>
<td>Calculates energy under section of PROB; Identical to GWHNRG of SYSINT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PROBX</td>
<td>PDCALC</td>
<td>------</td>
<td>Linearly interpolates PROB at a particular equivalent load; Identical to PROBX of SYSINT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASMTYS</td>
<td>SYSOPT</td>
<td>PVPER$</td>
<td>Assembles various calendar dates to and beyond horizon</td>
</tr>
<tr>
<td>Name</td>
<td>Called By</td>
<td>Calls</td>
<td>Purpose</td>
</tr>
<tr>
<td>--------</td>
<td>-----------</td>
<td>-------------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>WTPERS</td>
<td>SYSOPT</td>
<td>OPERR, ERASE</td>
<td>Writes out input for the various periods and system horizon totals</td>
</tr>
<tr>
<td>SETUPN</td>
<td>SYSOPT</td>
<td>ONLY$$, LOC, ERASE</td>
<td>Sets up costs and limits for remaining arcs in the network</td>
</tr>
<tr>
<td>SETUPT</td>
<td>SYSOPT</td>
<td>OPERR</td>
<td>Sets up input tape for Out of Kilter (O-O-K) Network Program</td>
</tr>
<tr>
<td>CONVRG</td>
<td>SYSOPT</td>
<td>CALSHP, ARCPRT, SETELE, NEWMRG, PVPER$$, LOC, OPERR, ERASE, OOKMAN$^1$, INCORE$^2$</td>
<td>Supervises inner cost convergence between OOKMAN (O-O-K Main Program) and INCORE Model</td>
</tr>
</tbody>
</table>

$^1$Out of Kilter (O-O-K) Network Program subroutines (see Appendix G)
$^2$INCORE Model subroutines (see QKCORE, Appendix H)
<table>
<thead>
<tr>
<th>Name</th>
<th>Called By</th>
<th>Calls</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>CALSHP</td>
<td>CONVRG</td>
<td>LOC</td>
<td>Calculates shape criterion for each period</td>
</tr>
<tr>
<td></td>
<td>CHKSHP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARCPRT</td>
<td>CONVRG</td>
<td>LOC</td>
<td>Prints O-O-K arcs after inner cost iteration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OPERR</td>
<td></td>
</tr>
<tr>
<td>SETELE</td>
<td>CONVRG</td>
<td>ERASE</td>
<td>Sets up new table of E's to be investigated by</td>
</tr>
<tr>
<td></td>
<td>OPTMUM</td>
<td></td>
<td>INCORE Model</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEWMRG</td>
<td>CONVRG</td>
<td>LOC</td>
<td>Sets up new table of λ's to be used by O-O-K</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OPERR</td>
<td></td>
</tr>
<tr>
<td>PVPERS</td>
<td>RDOPTN</td>
<td>---------</td>
<td>Calculates present (at base date) value of one</td>
</tr>
<tr>
<td>(PVINIT)</td>
<td>ASMTYS</td>
<td></td>
<td>dollar;</td>
</tr>
<tr>
<td></td>
<td>CONVRG</td>
<td></td>
<td>Has ENTRY PVINIT to initialize present value rate;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Identical to QKCORE version</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHKSHP</td>
<td>SYSOPT</td>
<td>CALSHP</td>
<td>Performs outer shape iteration and checks shape</td>
</tr>
<tr>
<td>(ONLY$$)</td>
<td>SETUPN</td>
<td>ARCPRT</td>
<td>criteria to evaluate acceptability;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SQUEEZ</td>
<td>Has ENTRY ONLY$$ to change objective function of</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LOC</td>
<td>O-O-K from shape to cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ERASE</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>OOKMAN(^1)</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\)Out of Kilter (O-O-K) Network Program subroutines (see Appendix G)
<table>
<thead>
<tr>
<th>Name</th>
<th>Called By</th>
<th>Calls</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQUEEZ</td>
<td>CHKSHP</td>
<td>LOC</td>
<td>Squeezes reactor period energy production range</td>
</tr>
<tr>
<td>EDTSHP</td>
<td>SYSOPT</td>
<td>LOC</td>
<td>Edits shape information and prints final altered energy limits</td>
</tr>
<tr>
<td>OPTMUM</td>
<td>SYSOPT</td>
<td>SETELE, INCORE(^1)</td>
<td>Supervises printing of optimum solution; Calls INCORE Model to get final nuclear costs at optimum; Totals all operating revenue requirements</td>
</tr>
<tr>
<td>LOC</td>
<td>SYSOPT</td>
<td>------</td>
<td>Calculates pointer to desired network arc</td>
</tr>
<tr>
<td></td>
<td>SETUPN</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CONVRG</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CALSHP</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ARCPRT</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NEWMRG</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CHKSHP</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SQUEEZ</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EDTSHP</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) INCORE Model subroutines (see QKCORE, Appendix H)
Table F.1--Continued

<table>
<thead>
<tr>
<th>Name</th>
<th>Called By</th>
<th>Calls</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPERR</td>
<td>SYSOPT</td>
<td>ICERRS(^1)</td>
<td>Prints error messages and chooses to terminate execution if severe error occurs (see Table F.2); Calls ICERRS to get final INCORE Model error edit</td>
</tr>
<tr>
<td></td>
<td>RDOPTN</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RDSTRG</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RDPERS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PDCALC</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SUBPLT</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WTPERS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SETUPT</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CONVRG</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ARCPRT</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NEWMRG</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMPTIM</td>
<td>SYSOPT</td>
<td>WHEN(^2)</td>
<td>Calls MIT internal clock routines to monitor execution time; Prints subroutine-to-subroutine transfer times; Has ENTRY STRTIM to start clock and ENTRY DAYTIM to print calendar date and time</td>
</tr>
<tr>
<td>(STRTIM)</td>
<td></td>
<td>TIMING(^2)</td>
<td></td>
</tr>
<tr>
<td>(DAYTIM)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ERASE</td>
<td>RDSTRG</td>
<td>-----</td>
<td>MIT Assembler Language program that sets arrays to zeroes rapidly</td>
</tr>
<tr>
<td></td>
<td>WTPERS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SETUPN</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ERASE</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SETELE</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CHKSHP</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) INCORE Model subroutines (see QKCORE, Appendix H)

\(^2\) WHEN and TIMING are MIT internal clock subroutines
Figure F.1
SYSOPT Flowchart

START

SYSOPT (MAIN)

INCORE INPUT

"STRATEGY"

SYSOPT INPUT

RDOPHT

RDSTRG

"COMPUTE"

SET UP NETWORK ARCS

OUT OF FILTER

ALTER MIN AND MAX $E_{rc0}$ FOR REJECTED PERIODS

TC & $\lambda_{rc}$

INCORE

$E_{rc}$

INNER ITERATION

$E_{rc}$

$E_{rc0}$

ALTER MIN AND MAX $E_{rc0}$

YES $E_{rc0}$

SQUEEZ

CHKSHP

OPTIMUM

IF "STRATEGY"

IF "NEW INCORE"

IF "STOP"

STOP

NEW IN-CORE REACTOR DATA INPUT

NEW STRATEGY INPUT

NO

ALL p ACCEPTED?

$e_{rc0}$ & TO
<table>
<thead>
<tr>
<th>Number*</th>
<th>Source</th>
<th>Action after Printing</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RDPERS</td>
<td>Terminate</td>
<td>PROB Data inconsistent</td>
</tr>
<tr>
<td>2</td>
<td>PDCALC SUBPLT</td>
<td>Terminate</td>
<td>Nuclear upper increment not consecutive or unit capacity &gt; minimum load</td>
</tr>
<tr>
<td>3</td>
<td>RDSTRG</td>
<td>Terminate</td>
<td>Reactor or Strategy IDNO's do not agree</td>
</tr>
<tr>
<td>4</td>
<td>SETUPT</td>
<td>Terminate</td>
<td>Number of arcs input to 0-0-K and equation in Figure F.2 do not agree</td>
</tr>
<tr>
<td>5</td>
<td>NEWMRG</td>
<td>RETURN</td>
<td>Incremental cost curve not monotonically increasing</td>
</tr>
<tr>
<td>6</td>
<td>SYSOPT RDOPTN WTPERS</td>
<td>Terminate</td>
<td>Improper input sequence and/or card; Input option outside limits</td>
</tr>
<tr>
<td>7</td>
<td>CONVRG</td>
<td>RETURN</td>
<td>MXITER reached without complete convergence</td>
</tr>
<tr>
<td>8</td>
<td>SYSOPT</td>
<td>Terminate</td>
<td>&quot;STOP&quot; Card 10 encountered in input or other severe error</td>
</tr>
<tr>
<td>9</td>
<td>CONVRG</td>
<td>RETURN</td>
<td>TC converged within TH$CON</td>
</tr>
</tbody>
</table>

*The error number initiating the OPERR print appears as the rightmost digit in the accumulated ERRCOD (which is printed as part of the message).*
<table>
<thead>
<tr>
<th>Number*</th>
<th>Source</th>
<th>Action after Printing</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>A(=10)</td>
<td>CONVRG</td>
<td>Terminate</td>
<td>INCORE and SYSOPT using different present value rates</td>
</tr>
<tr>
<td>B(=11)</td>
<td>ARCPRT</td>
<td>Terminate</td>
<td>No feasible solution to 0-0-K problem</td>
</tr>
<tr>
<td>C(=12)</td>
<td>RDSTRG RDPERS WTPERS</td>
<td>Terminate</td>
<td>Premature end to SYSINT data; some periods not read in</td>
</tr>
<tr>
<td>D(=13)</td>
<td>NEWMRG</td>
<td>RETURN</td>
<td>Cycle energy greater than its upper stretchout limit</td>
</tr>
</tbody>
</table>
Figure F.2

Nuclear Energy Network Structure

**Legend:**
- \( Z \) = number of periods
- \( R \) = number of reactors
- \( I \) = \( I_{aux} \)
- \( J \) = \( J_{FWRD} \) + \( J_{BKWRD} \)
- \( RC \) = total number of reactor-cycles

**Total:**
- \( \text{ARCS} = RC(I+1) + Z((J+1)R+1) + R+3 \)
- \( \text{NODES} = 2RC + Z(R+1) + 4 \)
Relative to INCORE interfacing, only four distinct points of SYSOPT-INCORE contact are necessary to ensure compatibility with general CORSOM's:

1) SYSOPT itself calls ICNPUT [if an "INCORE INPUT" Control Card is encountered (See Section F.2)] to permit an INCORE Model to read any data required by it (e.g., core initial conditions and cost parameters).

2) Subroutine CONVRG calls INCORE subroutine with the arguments specified in Table F.3. This call is executed many times as this is the actual inner iteration. The important results are \( \text{RTC} \) (returned as RTC) and the \( \lambda_{rc} \) (appearing "sandwiched" between the pertinent \( E_{rc} \) and \( E_{rc} + \Delta \) in array ELAME as in Section H.1.3.

3) Subroutine OPTIMUM also calls INCORE subroutine per Table F.3, but only to evaluate the final optimum reload designs in more detail. COMMON area /PRINTS/ is used for passing any print options or dataset reference numbers.

4) Finally, subroutine OPERR calls INCORE error subroutine ICERRS to permit printing final edit of any INCORE Model errors encountered during the SYSOPT optimization.

When SYSOPT and O-O-K have been link-edited with the particular simulator QKCORE, core storage requirements (See Section 4.6) can be reduced by 125 K bytes of storage or
Table F.3
Interfacing of SYSOPT and an INCORE Model

<table>
<thead>
<tr>
<th>Variable</th>
<th>Supplied By</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDNUM</td>
<td>SYSOPT</td>
<td>Unit IDNO</td>
</tr>
<tr>
<td>NCYCIN</td>
<td>SYSOPT</td>
<td>Number of cycles at least partially within horizon</td>
</tr>
<tr>
<td>NCYCXS</td>
<td>SYSOPT</td>
<td>Number of whole cycles specified beyond horizon</td>
</tr>
<tr>
<td>NCYCTO</td>
<td>SYSOPT</td>
<td>$\text{NCYCIN} + \text{NCYCXS} = \text{total}$</td>
</tr>
<tr>
<td>TSY(1) to TSY(NCYCTO)</td>
<td>SYSOPT</td>
<td>Calendar time at start of cycle, years</td>
</tr>
<tr>
<td>TEY(1) to TEY(NCYCTO)</td>
<td>SYSOPT</td>
<td>Calendar time at end of cycle, years</td>
</tr>
<tr>
<td>NECBAL(1) to NECBAL(NCYCTO)</td>
<td>SYSOPT</td>
<td>Position of key $E_{rc}$ within ELAME representing $E_{rc}^t$ (See Section H.1.3)</td>
</tr>
<tr>
<td>ELAME(1,1) to ELAME(2n,1,NCYCTO)</td>
<td>E by SYSOPT, $\lambda$ by INCORE</td>
<td>$E_{rc}$ cycle energy and $\lambda_{rc}$ incremental costs (See Section H.1.3)</td>
</tr>
<tr>
<td>MXESX2</td>
<td>SYSOPT</td>
<td>$n_{\lambda}$ number of $\Delta$ stair-steps in each $\lambda_{rc}$ incremental cost curve</td>
</tr>
<tr>
<td>ECHDOV</td>
<td>SYSOPT</td>
<td>Holdover energy, GWHe</td>
</tr>
<tr>
<td>Variable</td>
<td>Supplied By</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>RTC</td>
<td>INCORE</td>
<td>Total nuclear fuel cost including appropriate fraction of cost of cycle split by horizon, 10^3 dollars</td>
</tr>
<tr>
<td>PVR</td>
<td>INCORE</td>
<td>x, present value rate used by INCORE, fraction per year</td>
</tr>
<tr>
<td>YBS</td>
<td>INCORE</td>
<td>Calendar time base date of present valuing in INCORE, years</td>
</tr>
<tr>
<td>ECUPLM(l) to ECUPLM(NCYCTO)</td>
<td>INCORE</td>
<td>Upper limit of energy extractable from each cycle that has reload enrichment fixed, GWHe</td>
</tr>
<tr>
<td>TOY(l) to TOY(NCYCTO)</td>
<td>SYSOPT</td>
<td>Length of time that unit is operating during cycle, years</td>
</tr>
</tbody>
</table>
one-third of total (with negligible increase in computing time) by using the overlay structure of Figure F.3.

F.1.3 Altering Dataset Reference Numbers

Table F.4 presents the dataset reference numbers for each input/output device, their meaning and instructions for altering them for other computer installations.
Figure F.3

"SYSOPT + Out of Kilter + QKCORE" Overlay Structure

NOTE: EITHER SEGMENT 4 OR 8 DETERMINES MAXIMUM STORAGE REQUIREMENT.

SEGMENT 1
Subrs.
- MAIN(SYSOPT)
- LOC
- OPERR
- CMPTIM
- INCORE
- UNTCOS
- UFGVAL
- ICERRS
- PVPER$
- [SYSTEMS]
- [ROUTINES]

Commons
- /OPTLIM/
- /RCDAT/
- /FINALS/
- /PDPERM/
- /KC/
- /KU/
- /KL/
- /OOKCOM/
- /FXDDAT/

SEGMENT 2
Subrs.
- RDOPTN
- RDSTRG
- REDCOR

COMMON AREAS /IJ/, /IL/.

SEGMENT 3
Subrs.
- RDPERS
- PDCALC
- SUBPLT
- GWHRG
- PROBX
- /PROB/

Commons
- /PDTEMP/
- /SYSTEMS ROUTINES/
- /RCRDAT/
- /FINALS/
- /PDPERM/
- /KC/
- /KU/
- /KL/
- /OOKCOM/
- /FXDDAT/

SEGMENT 4
Subrs.
- RDPERS
- PDCALC
- SUBPLT
- GWHRG
- PROBX
- /PROB/

Commons
- /PDTEMP/
- /SYSTEMS ROUTINES/
- /RCRDAT/
- /FINALS/
- /PDPERM/
- /KC/
- /KU/
- /KL/
- /OOKCOM/
- /FXDDAT/

SEGMENT 5
Subrs.
- ASMTYS
- WTPERS
- SETUPN
- SETUPT

Commons
- /ASMTYS/
- /WTPERS/
- /SETUPN/
- /SETUPT/

SEGMENT 6
Subrs.
- CONVRG
- CALSHP
- ARCPRT
- SETELE
- NEWMGR
- SQUEEZ
- FULSIM
- CONSTS
- NXTIRR
- IRRDAT
- CSTBAT
- PRTTOP
- EMPRCL
- MAIN
- PREDAT
- ASSEM1
- ASSEM2

Commons
- /CONVRG/
- /CALSHP/
- /ARCPRT/
- /SETELE/
- /NEWMGR/
- /SQUEEZ/
- /FULSIM/
- /CONSTS/
- /NXTIRR/
- /IRRDAT/
- /CSTBAT/
- /PRTTOP/
- /EMPRCL/
- /MAIN/
- /PREDAT/
- /ASSEM1/
- /ASSEM2/

SEGMENT 7
Commons
- /ARCASY/
- /MAKEJL/
- /NODASY/
- /READER/
- /TRANSL/
- /KILTER/
- /OUTPUT/
- /EDTSHP/
- /OPTMUM/

SEGMENT 8
Commons
- /ARCASY/
- /MAKEJL/
- /NODASY/
- /READER/
- /TRANSL/
- /KILTER/
- /OUTPUT/
- /EDTSHP/
- /OPTMUM/

SEGMENT 9
Commons
- /ARCASY/
- /MAKEJL/
- /NODASY/
- /READER/
- /TRANSL/
- /KILTER/
- /OUTPUT/
- /EDTSHP/
- /OPTMUM/

* COMMON AREAS /IJ/, /IL/, /JL/ MUST OCCUPY CONSECUTIVE CORE STORAGE (SEE SECTION G.2)
<table>
<thead>
<tr>
<th>Fortran Symbol</th>
<th>Meaning</th>
<th>Current Value</th>
<th>Instructions for Altering</th>
</tr>
</thead>
<tbody>
<tr>
<td>RD</td>
<td>Card Reader</td>
<td>5</td>
<td>See BLOCK DATA subroutine</td>
</tr>
<tr>
<td>WT</td>
<td>Output Printer</td>
<td>6</td>
<td>See BLOCK DATA subroutine</td>
</tr>
<tr>
<td>SIOT</td>
<td>SYSINT-to-SYSOPT Output</td>
<td>8</td>
<td>Input Card 4 and any //G.FT08F001 Data Definition Cards (see Figure F.4)</td>
</tr>
<tr>
<td>NPIN</td>
<td>Network Program Input</td>
<td>9</td>
<td>Input Card 4 and any //G.FT09F001 Data Definition Cards (see Figure F.4)</td>
</tr>
<tr>
<td>NPOT</td>
<td>Network Program Output</td>
<td>10</td>
<td>Input Card 4 and any //G.FT10F001 Data Definition Cards (see Figure F.4)</td>
</tr>
</tbody>
</table>
F.2 SYSOPT Input Specifications

Table F.5 presents complete SYSOPT input specifications. "NEW" Card 1 signals a call to ICNPUT to read the INCORE Model data module. After the INCORE input, "STRATEGY" Card 2 heads the SYSOPT input data module (Cards 3-8). The next module read is SYSINT-to-SYSOPT output whether on disk, tape or card. A "COMPUTE" Card 9 initiates the optimization. If no other modules are to be input and/or executed, a "STOP" Card 10 terminates SYSOPT execution.
### Table F.5
**SYSOPT Input Specifications**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Card 1</td>
<td>...</td>
<td>1-12</td>
<td>&quot;INCORE INPUT&quot; Control card signifies following group of cards intended as input to INCORE Model</td>
</tr>
</tbody>
</table>

**Note:** Input deck for INCORE Model is inserted here.

Card 2

<table>
<thead>
<tr>
<th>...</th>
<th>1-8</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;STRATEGY&quot; Control Card signifies SYSOPT input to follow</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Card 3

<table>
<thead>
<tr>
<th>NPM</th>
<th>3</th>
<th>2X,L1</th>
<th>Nuclear power management strategy? (See Card 22 of SYSINT Input Specifications, Table E.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDSTRG</td>
<td>4-10</td>
<td>I7</td>
<td>IPLACE *10 + IDSTRG of SYSINT (See Card 22 of SYSINT Input Specifications, Table E.5)</td>
</tr>
</tbody>
</table>

**Note:** These 8 alphameric characters must match membername of SYSINT-to-SYSOPT output which, likewise, must match membername on SIOT Data Definition Card (See Figure F.4).

<table>
<thead>
<tr>
<th>NRCRS</th>
<th>11-15</th>
<th>I5</th>
<th>Number of reactors in SYSINT strategy, &lt; 15</th>
</tr>
</thead>
</table>

Card 4

<table>
<thead>
<tr>
<th>SIOT</th>
<th>1-5</th>
<th>I5</th>
<th>Dataset reference number for SYSINT-to-SYSOPT output, ≠ WT</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPIN</td>
<td>6-10</td>
<td>I5</td>
<td>Dataset reference number for 0-0-K Network Program input, ≠ RD or WT</td>
</tr>
<tr>
<td>NPOT</td>
<td>11-15</td>
<td>I5</td>
<td>Dataset reference number for 0-0-K Network Program output ≠ RD</td>
</tr>
<tr>
<td>Variable</td>
<td>Columns</td>
<td>Format</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>---------</td>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>PARCAL</td>
<td>16-20</td>
<td>I5</td>
<td>Last arc type printed for all inner SYSOPT iterations (See Figure F.2), ≥ 0</td>
</tr>
<tr>
<td>PARCON</td>
<td>21-25</td>
<td>I5</td>
<td>Last arc type printed for converged inner iteration (See Figure F.2), ≥ 0</td>
</tr>
<tr>
<td>PARCOP</td>
<td>26-30</td>
<td>I5</td>
<td>Last arc type printed for accepted global optimum (See Figure F.2), ≥ 0</td>
</tr>
<tr>
<td>CORDTL</td>
<td>31-35</td>
<td>I5</td>
<td>INCORE detailed output desired for accepted global optimum? 0 = No 1 = Yes</td>
</tr>
<tr>
<td>OPRCOR(1) to OPRCOR(6)</td>
<td>36-41</td>
<td>6L1</td>
<td>INCORE print parameters for use by OPTMUM (See Card 2, QKCORE Input Specifications, Table H.6) F = No T = Yes</td>
</tr>
</tbody>
</table>

Fortran symbol in

<table>
<thead>
<tr>
<th>SYSOPT</th>
<th>QKCORE</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPRCOR(1)</td>
<td>= RELCST</td>
</tr>
<tr>
<td>OPRCOR(2)</td>
<td>= INCCST</td>
</tr>
<tr>
<td>OPRCOR(3)</td>
<td>= BALCST</td>
</tr>
<tr>
<td>OPRCOR(4)</td>
<td>= NBLCST</td>
</tr>
<tr>
<td>OPRCOR(5)</td>
<td>= PIRDAT</td>
</tr>
<tr>
<td>OPRCOR(6)</td>
<td>= PBATCS</td>
</tr>
</tbody>
</table>

**Card 5**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVRATE</td>
<td>1-7</td>
<td>F7.0</td>
<td>x, present value rate, fraction per year</td>
</tr>
<tr>
<td>YBASE</td>
<td>8-14</td>
<td>F7.0</td>
<td>Calendar time base date for present valuing, years</td>
</tr>
<tr>
<td>YSTART</td>
<td>15-21</td>
<td>F7.0</td>
<td>Calendar time at start of Period 1, years</td>
</tr>
<tr>
<td>PCONVG</td>
<td>22-28</td>
<td>F7.0</td>
<td>$100 \times \left</td>
</tr>
<tr>
<td>Variable</td>
<td>Columns</td>
<td>Format</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>---------</td>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>TH$CON</td>
<td>29-35</td>
<td>F7.0</td>
<td>$\frac{TC^t - TC^{t+1}}{TC^t} &lt; TH$CON, total nuclear fuel cost convergence criterion, $10^3$ $</td>
</tr>
<tr>
<td>PCDELA</td>
<td>36-42</td>
<td>F7.0</td>
<td>$\gamma$, fraction of estimated correction applied to reactor production limits, per cent</td>
</tr>
<tr>
<td>REJLVL</td>
<td>43-50</td>
<td>F8.0</td>
<td>$v_{REJ}^2$, shape rejection criterion for $S^2 - W^2$</td>
</tr>
<tr>
<td>NPERS</td>
<td>51-55</td>
<td>I5</td>
<td>$Z$, number of periods of SYSINT strategy to be included in horizon, $\leq$ NPERS $\leq 100$ in SYSINT</td>
</tr>
<tr>
<td>GESFRS</td>
<td>56-60</td>
<td>I5</td>
<td>Initial guess option for starting optimization:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>=0, No guess at all (No Card 6's)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>=1, Use SYSINT output $E_{rcp}$ (No Card 6's)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>=2, $\lambda_{rc}$ entered on Card 6's</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>=3, Estimated $E_{rc}$ entered on Card 6's</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>=4, Previous $E_{rc}^*$ solution entered on Card 6's</td>
</tr>
<tr>
<td>MXITER</td>
<td>61-65</td>
<td>I5</td>
<td>Maximum total number of inner iterations to be allowed, $\leq 100$</td>
</tr>
<tr>
<td>IAUX</td>
<td>66-70</td>
<td>I5</td>
<td>Total number of auxiliary arcs (Types 2 and 3 of Figure F.2) per reactor-cycle, used to form stair-step $\lambda_{rc}$ curve, $3 \leq IAUX \leq 19$</td>
</tr>
<tr>
<td>JFRWRD</td>
<td>71-75</td>
<td>I5</td>
<td>Number of forward arcs (part of Type 7) per reactor per period, $2 \leq JFRWRD \leq 6$</td>
</tr>
</tbody>
</table>
Variable Columns Format Description

JBKWRD .76-80 I5 Number of backward arcs (rest of Type 7) per reactor per period, For balance, JBKWRD = JFRWRD-1 is best, 1 < JBKWRD < 6

Note: Total number of network arcs (See Figure F.2) cannot exceed MXARCS (=3500). Total number of network nodes cannot exceed MXNODS (=700).

Note: If GESFRS > 2, there must be NRCRS of Card 6, one for each reactor.

Card 6 (if GESFRS = 2)

ELAME(NR,1) 1-80 20F4.0 \( \lambda_{rc} \) incremental cost guess, to ELAME \( \$/GWH \equiv \$/MWH \times 10^3 \) (NR,NCYCIN)

Card 6 (if GESFRS > 2)

ELAME(NR,1) 1-80 20I4 \( E_{rc} \) cycle energy guess or to ELAME to Card 6 solution, GWH (NR,NCYCIN)

Card 7

NMESH 1-5 I5 Number of different \( \Delta \) energy increment (step size) to be used in approaching TC*,0, 1 < NMESH < 15

MESH(1) 6-80 15I5 \( \Delta \) energy increment (step size), largest first, GWH to MESH(NMESH)

Note: There must be NRCRS of Card 8, one for each reactor.

Card 8

IDNO 1-4 I4 Reactor IDNO, must agree with SYSINT's IDNO for same unit.

INSTAT 5-7 I3 Initial state of unit, i.e., maintenance status during "period" immediately preceding first period of strategy

=0 , did not exist
=1 , down for refueling
=2 , on-line
<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CYCXS</td>
<td>8-10</td>
<td>I3</td>
<td>Number of excess cycles included beyond horizon</td>
</tr>
<tr>
<td>GW HOLD</td>
<td>11-15</td>
<td>I5</td>
<td>$E_{r,C,Z+1}$ Cycle energy held over beyond horizon for split cycle, GWH</td>
</tr>
<tr>
<td>DY HOLD</td>
<td>16-22</td>
<td>F7.4</td>
<td>$T_{Z+1}'$ Time remaining to next refueling beyond horizon for split cycle, years</td>
</tr>
<tr>
<td>DY DWN</td>
<td>...</td>
<td>F6.4</td>
<td>Downtime between excess cycles, years</td>
</tr>
<tr>
<td>DY UP</td>
<td>...</td>
<td>F6.4</td>
<td>Uptime for this excess cycle, years</td>
</tr>
<tr>
<td>GWH XS</td>
<td>...</td>
<td>I6</td>
<td>$E_{r,C+1}$ Excess cycle energy, GWH</td>
</tr>
</tbody>
</table>

Note: Continue until CYCXS number of excess cycles have been specified.

Note: SYSINT-to-SYSOPT output is inserted here if SIOT = RD = 5 at MIT (See Section E.1.3).

Note: "COMPUTE" Control Card 9 may be omitted to only check input of strategy or obtain present value of SYSINT cost results.

Card 9

... 1-7 ... "COMPUTE" Control Card initiates optimization

Note: Next card may be "INCORE INPUT" Card 1, "STRATEGY" Card 2 or "STOP" Card 10 with input sequence reverting to appropriate point in card sequence.

Card 10

... 1-4 ... "STOP" Control Card to terminate execution of SYSOPT for this computer run.
F.3  **SYSOPT Sample Problem**

Figure F.4 presents the input deck used for optimizing Strategy 2 in Case I of Chapter 5. **SYSINT-to-SYSOPT** output is provided on Disk.
F.4 **SYSOPT Source Listing**

The following is a Fortran IV source listing of the SYSOPT code (included only in MIT library copies).
APPENDIX  \textbf{G}  
\textbf{Out of Kilter Network Program}  

G.1 \textit{Out of Kilter Discussion}  

The complete Out of Kilter Network Program was graciously provided to the author by the Flight Transportation Laboratory at MIT. Only minor modifications were made to the program to facilitate on-line merging with SYSOPT. These modifications are transparent to any user interested only in the Out of Kilter Program itself, i.e., for solving network programming problems in other contexts. Figure G.1 is provided as a guide to the computer storage requirements necessary to run the program for various size problems (see Sub-section 13 of Section G.2).

Because of the program's generality, the original input manual (45) is included here with only minor editorial revisions.
Figure G.1

Core Storage Requirements for Out-of-Kilter Network Program

REGARDLESS OF NODES AND ARCS, APPROXIMATELY 45K ADDITIONAL BYTES REQUIRED FOR PROGRAM LOGIC AND COMPUTER SUPERVISOR

200K BYTES OF CORE STORAGE FOR ARRAYS ONLY
G.2 Out of Kilter Input Specifications

IBM /360 OUT OF KILTER NETWORK FLOW ROUTINE
DESCRIPTION FOR THE USER

Table of Contents

Section
1. Introductory Notes
2. Formulation
3. Data
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6. Jobs with More Than One Run
7. Save and Alter Run
8. Other Program Options
9. Output
10. Program Messages
11. Program Operation Notes
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1. Introductory Notes

This writeup is intended for the user of the "Out of Kilter" program which has been written for the IBM system 360 model 65. The program has been successfully run at the MIT Computation Center.

Both the program and the writeup are based on the SHARE routine RS_OKFI and its corresponding writeup.

The FORTRAN subprograms are written in FORTRAN IV (G level). The assembly language subprograms use the extended mnemonic branching instruction codes and the macros SAVE and RETURN.

The program and this writeup were prepared by Amos Levin, Flight Transportation Laboratory, MIT, August 1967.
2. Formulation

A computer routine for the solution of "network flow" programs -- problems of finding those flows of an homogeneous commodity through a capacitated network minimizing the sum of the linear costs of flow through each arc -- is herein described. The computational algorithm employed is described in the book "Flows in Networks", L.R. Ford and D.R. Fulkerson, Princeton University Press, 1962, pp.162-169.

The network in question consists of nodes designated by i or j, and a certain collection of arcs joining pairs of nodes. The arc i→j is thought of as directed from i to j.

With each arc in the network is associated the following four integer quantities.

$c_{ij}$ the cost of one unit of flow from i to j along arc i→j;
$u_{ij}$ the upper bound on the amount of flow along the arc i→j;
$l_{ij}$ the lower bound on the amount of flow along the arc i→j;
$x_{ij}$ the quantity of flow along the arc i→j.

The network flow problem is that of determining $x_{ij}$ (for all arcs i→j of the network) such that

1. $l_{ij} \leq x_{ij} \leq u_{ij}$ (all arcs i→j),
2. the net flow into any node (generally zero) remains fixed throughout the solution of the problem, and
3. $\sum_{ij} c_{ij} x_{ij}$ is minimized.
### Data

#### Data Format

A node may be represented by any combination of six Hollerith characters (at least one of which is neither zero nor blank); i and j below are such combinations. (Note that for node names a blank is a character, and different from a zero.) The numerical data above are represented as right-justified integers in the appropriate fields. All data pertaining to one arc are entered on one card as follows:

<table>
<thead>
<tr>
<th>1..6</th>
<th>7..12</th>
<th>13..18</th>
<th>19,20</th>
<th>21..30</th>
<th>31..40</th>
<th>41..50</th>
<th>51..60</th>
<th>61..80</th>
</tr>
</thead>
<tbody>
<tr>
<td>blank</td>
<td>i</td>
<td>j</td>
<td>free to use</td>
<td>c&lt;sub&gt;ij&lt;/sub&gt;</td>
<td>u&lt;sub&gt;ij&lt;/sub&gt;</td>
<td>η&lt;sub&gt;ij&lt;/sub&gt;</td>
<td>x&lt;sub&gt;ij&lt;/sub&gt;</td>
<td>free to use</td>
</tr>
</tbody>
</table>

Leading zeros in the numeric fields need not be entered, nor need any figures where zero is desired.

Of course, fields 7-50 contain constants for the stated problem. Entry of the "x<sub>ij</sub>" is optional, constituting only an initial guess at the solution.

An optional initial set of node prices η<sub>i</sub> may be entered. These are entered one per card as follows:

<table>
<thead>
<tr>
<th>1 .. 6</th>
<th>7 .. 12</th>
<th>13 .. 20</th>
<th>21 .. 30</th>
<th>31 ..... 80</th>
</tr>
</thead>
<tbody>
<tr>
<td>blank</td>
<td>i</td>
<td>free to use</td>
<td>η&lt;sub&gt;i&lt;/sub&gt;</td>
<td>free to use</td>
</tr>
</tbody>
</table>

#### Assembly of Data

The data just described is put together in the following way:

1) All arcs <i,j> having a given first node i must be adjacent in the deck. (No other requirement on their order is made.)
2) The arc cards are preceded by two cards, the first being the title card and the second bearing the word "ARCS" in the field 1-4. The title card should be blank in column 1 and may have any Hollerith punches in columns 2-80.

3) If no node prices are given, the arc cards are followed by a card bearing "END" in 1-3.

4) If node prices are given, the arcs are followed by a card bearing "NODES" in 1-5; the node cards follow this, and all the cards are followed by the END card of (3).
4. Control Cards for Standard Run

Input, computation, and output are effected by control cards whose punching in the field 1-12 controls the operation of the routine. Punching always begins in column 1, and there is one blank between English words. The first card of the deck which follows the program deck must be the control card READY.

Following the "READY" card must be one of the two control cards

CARD S or TAPE

If "TAPE", the assembled data described in the previous section should be on the reserved input tape. If "CARDS", the assembled data should immediately follow this control card.

Next may be placed any combination of the three output control cards

OUTPUT TAPE
OUTPUT PRINTER
OUTPUT PUNCH

which will cause the types of output described in Section 8. At least one OUTPUT control card must be included in the data set.

Next is placed the card

COMPUTE

which causes computation to begin.

The last card in the deck must be the control card

PAUSE

which terminates the job.
5. Example

The example which follows is a modification of the one given in the book "Flows In Networks", L.R. Ford and D.R. Fulkerson, Princeton University Press, 1962, pp.123-127. Costs and bounds for the arcs can be found in the data listing on the next page. Since the cost on the arc $TS$ is very low (negative) compared to the costs on the other arcs, the routine finds the maximal flow that minimizes costs from $S$ to $T$. 
### READY
### CARDS
### F. AND F. EXAMPLE 1
### ARCS

<table>
<thead>
<tr>
<th></th>
<th>X1</th>
<th>X2</th>
<th>X3</th>
<th>X4</th>
<th>X5</th>
<th>X6</th>
<th>X7</th>
<th>X8</th>
<th>X9</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>3</td>
<td>50</td>
<td>35</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S</td>
<td>6</td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S</td>
<td>8</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X1</td>
<td>2</td>
<td>50</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X1</td>
<td>2</td>
<td>25</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X2</td>
<td>2</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X2</td>
<td>1</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X2</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X2</td>
<td>8</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X3</td>
<td>1</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X3</td>
<td>3</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X3</td>
<td>9</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X4</td>
<td>8</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X4</td>
<td>5</td>
<td>60</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X5</td>
<td>1</td>
<td>10</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X6</td>
<td>2</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X6</td>
<td>4</td>
<td>80</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X7</td>
<td>2</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X7</td>
<td>3</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X8</td>
<td>3</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X9</td>
<td>3</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>T</td>
<td>5</td>
<td>-10000</td>
<td>85</td>
<td>25</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### END
### OUTPUT PRINTER
### OUTPUT TAPE
### COMPUTE
### PAUSE

The control card setup described in Section 3 applies to jobs with only one run. By a "job", we mean all that is done in one pass at the computer; that is, any work that can be done without manual interference with the computer and, in addition, without inputting the program instructions into the computer more than once. By a "run", we mean that which is involved in the solution of one problem.

For multiple run jobs, the standard input for each run is as described in Section 3 with the "PAUSE" card removed. Runs may be stacked one after another. Only one "PAUSE" card may be used, and it is always placed after the "COMPUTE" card of the final run.

Each run begins with a "READY" card or a "SAVE" card as described in Section 6. Each run ends with a "COMPUTE" card. The job ends with a "PAUSE" card.
7. Save and Alter Run

In Section 3, the standard run beginning with the "READY" card was described. In Section 5, it was noted that these runs may be stacked, one after another. Frequently it is desired to execute a run in which only relatively few $c_{ij}$, $u_{ij}$ or $l_{ij}$ are changed, but in which the arc configuration remains the same. In this event, a "Save and Alter" procedure may be followed. A "Save and Alter" run may be any run except the first. The control card setup for this type of run is as follows.

The first card of the run must be the control card SAVE which initiates a new run without destroying the results of the previous run.

The second card is the title card, which may have any Hollerith punches in it, except that column 1 should be blank.

Next are placed the "OUTPUT" cards as mentioned in Section 3 and described in Section 8.

Next are placed any number of "ALTER" cards. Each "ALTER" card has the following format:

```
<p>| | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1..6</td>
<td>7..12</td>
<td>13..18</td>
<td>19,20</td>
<td>21..30</td>
<td>31..40</td>
<td>41..50</td>
<td>51..60</td>
<td>61..80</td>
</tr>
<tr>
<td>ALTER</td>
<td>i</td>
<td>j</td>
<td>n_{ij}</td>
<td>c_{ij}</td>
<td>u_{ij}</td>
<td>l_{ij}</td>
<td>Δf_{ij}</td>
<td>free to use</td>
</tr>
</tbody>
</table>
```
i and j are the source and sink nodes of an arc which is in core storage; that is, one which was used on the preceding "READY" run. \( n_{ij} \) may be left blank if there is only one arc \( ij \). If there is more than one arc \( ij \), then \( n_{ij} \) gives the number of this arc as to whether it was the 1st, 2nd, 3rd, etc. arc \( ij \) which was read into memory in the applicable "READY" run. \( c_{ij}, u_{ij} \) and \( \ell_{ij} \) are the new values of these same quantities for this arc.

\( \Delta f_{ij} \) is usually zero (or blank). It is the change in the flow out of node i and into node j. Note that inputting a new \( x_{ij} \) is meaningless, since \( x_{ij} \) on input is a guess, and guessing a value of \( x_{ij} \) on an alter run would only upset the conservation of flow from the nodes. Hence inputting a non-zero \( \Delta f_{ij} \) is a means of deliberately upsetting the flow conservation. It will change \( x_{ij} \) to \( x_{ij} + \Delta f_{ij} \).

The last card of the run must be the control card

```
COMPUTE
```

which causes computation to begin.

Note that any number of "Save and Alter" runs may follow one "READY" run. The effects of each "Save and Alter" are cumulative.

The program also allows "ALTER" cards to be placed after the "OUTPUT" cards and before the "COMPUTE" card on a "READY" run. This "Ready and Alter" run is useful when data is on tape and a few changes in the value of \( c, u, \) and \( \ell \) are needed before the run is to be executed.
8. Other Program Options

In the standard run, the program requires that every node be a first node for some arc and be a second node for some other arc. This is the standard network problem. Another type of problem allows arcs to end at nodes at which no arcs begin. These sinks are designated by the program as "dead end arcs." There may also be source nodes at which no arc terminates. This type of problem is designated a "transportation" problem and the requirement that at least one arc begin at each node and end at each node is ignored by the program.

The reserved input tape may have data for several jobs stacked on it. There are no ends of file on this tape except at the end of all data; the program knows when it is at the end of the data for one run by sensing the "END" card record. In certain cases, it may be desirable to pass over some data packages while processing a job. In this event, the control card "SKIP" is used.

The general "READY" type run is now described.

The first card must be the control card

```
READY
```

An optional card which must follow the "READY" card if this is a transportation problem, is the control card

```
TRANSPORTATION
```

Also optional is the control card

```
SKIP
```

which is used to cause the reserved input tape to skip one package of assembled data. As many "SKIP" cards are used as are needed to skip the desired number of packages of assembled data. The "SKIP" cards and the "TRANSPORTATION" card may be in any order immediately following the "READY" card.
Following the above cards must be one of the two control cards
CARDS or TAPE
These cards are as described in Section 3.

The data package follows the "CARDS" control card. Following
the data package, or the control card "TAPE" where there is
no data package with the control cards, may be an optional title
card. If this is included, it supersedes the title card on the
data package.

Next may be placed any number of "OUTPUT" cards as described
in Section 8.

Next may be placed any number of "ALTER" cards as described
in Section 6.

The last card in the run must be the control card
COMPUTE
which causes computation to begin.
9. Output

The type of output is controlled by one or more of four control cards. The four control cards are

a) OUTPUT PRINTER
b) OUTPUT TAPE
c) OUTPUT PUNCH
d) OUTPUT NODES

The "OUTPUT PRINTER" control card causes output to be written on the system output device. This output is written for printing on the peripheral printer under program control. The system output device is denoted in the program by the symbol "KO", and KO has the value 6 in the version of the program submitted.

The data for each arc are printed horizontally on the page. The data for one arc, \(ij\), are printed in the following order:

1) node name i
2) node name j
3) \(c_{ij}\), the unit cost of arc \(ij\)
4) \(u_{ij}\), the upper bound of the quantity of flow through arc \(ij\)
5) \(l_{ij}\), the lower bound of the quantity of flow through arc \(ij\)
6) \(x_{ij}\), the quantity of flow in the arc \(ij\)
7) "FLOW" = \(c_{ij} x_{ij}\), the total cost of \(x_{ij}\) units at the cost \(c_{ij}\)
8) \(\pi_i\), the node price of node i
9) \(\pi_j\), the node price of node j
10) \(\zeta_{ij}\), the quantity \(\pi_i + c_{ij} - \pi_j\)
11) The letter "K", the letter "N" or nothing.

The letter "K" is printed if all the arcs are in kilter. The letter "N" is printed if this arc could not be brought into kilter,
indicating that the problem has no feasible solution. Nothing is printed in all other cases.

The "OUTPUT TAPE" control card causes output to be written on the reserved output tape. This output may be printed peripherally using single space (or double space) control. It may also be punched peripherally, and the cards gotten thereby will be substantially the same as the cards gotten from the "OUTPUT PUNCH" option described below. The information from the "OUTPUT TAPE" option is the same as that from the "OUTPUT PRINTER" option, except that items 8), 9), and 10), are not output. This output is compatible with the input "TAPE" option.

The "OUTPUT PUNCH" option gives items 1) through 7) on the on-line punch. This option is generally very time consuming except on short problems.

Any of the above three options may be used in combination on any one problem. At least one OUTPUT control card must be included in each data set.

The "OUTPUT NODES" option will output a list of node prices in addition to the arc information on the tape or punch options. This option will have no effect on the printer output option.

All of the output on the reserved output tape and on the punch is compatible with the input to the problem. The "OUTPUT PRINTER" output is not compatible with the input.

In addition to the above, all control card information is written on the peripheral printer device, with the exception of the
"COMPUTE" control card for which is substituted a count of the arcs and the nodes. The messages in Section 9 are all written on the system output device also.

On the following two pages are shown the "OUTPUT PRINTER" results of the example given in Section 4. "Flow" is $c_{ij} x_{ij}$. "Total system contribution" is the optimal value of the objective function $\sum c_{ij} x_{ij}$. Note that the first page contains information that would be on the system output device regardless of whether "OUTPUT PRINTER" is requested.
READY
CARDS
    F. AND F. EXAMPLE 1
ARCS
OUTPUT PRINTER
OUTPUT TAPE
NO OF ARCS= 22 NO OF NODES= 11
THIS RUN OUTPUT TO TAPE
**Example 1**

<table>
<thead>
<tr>
<th>ARC</th>
<th>COST</th>
<th>UPPER</th>
<th>LOWER</th>
<th>X</th>
<th>FLOW</th>
<th>PI1</th>
<th>PI2</th>
<th>CBAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>X1</td>
<td>3</td>
<td>40</td>
<td>35</td>
<td>30</td>
<td>150</td>
<td>17</td>
<td>-1 K</td>
</tr>
<tr>
<td>S</td>
<td>X2</td>
<td>6</td>
<td>30</td>
<td>0</td>
<td>20</td>
<td>120</td>
<td>13</td>
<td>-3 K</td>
</tr>
<tr>
<td>S</td>
<td>X3</td>
<td>8</td>
<td>15</td>
<td>0</td>
<td>15</td>
<td>120</td>
<td>13</td>
<td>0 K</td>
</tr>
<tr>
<td>X1</td>
<td>X2</td>
<td>2</td>
<td>50</td>
<td>0</td>
<td>25</td>
<td>50</td>
<td>17</td>
<td>0 K</td>
</tr>
<tr>
<td>X1</td>
<td>X4</td>
<td>2</td>
<td>25</td>
<td>0</td>
<td>25</td>
<td>50</td>
<td>17</td>
<td>-1 K</td>
</tr>
<tr>
<td>X2</td>
<td>X3</td>
<td>2</td>
<td>15</td>
<td>0</td>
<td>15</td>
<td>30</td>
<td>19</td>
<td>-3 K</td>
</tr>
<tr>
<td>X2</td>
<td>X4</td>
<td>1</td>
<td>50</td>
<td>0</td>
<td>5</td>
<td>5</td>
<td>19</td>
<td>0 K</td>
</tr>
<tr>
<td>X2</td>
<td>X5</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>30</td>
<td>19</td>
<td>25</td>
<td>-3 K</td>
</tr>
<tr>
<td>X2</td>
<td>X7</td>
<td>8</td>
<td>15</td>
<td>0</td>
<td>15</td>
<td>120</td>
<td>19</td>
<td>0 K</td>
</tr>
<tr>
<td>X3</td>
<td>X5</td>
<td>1</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>24</td>
<td>25</td>
<td>0 K</td>
</tr>
<tr>
<td>X3</td>
<td>X8</td>
<td>3</td>
<td>20</td>
<td>0</td>
<td>20</td>
<td>60</td>
<td>24</td>
<td>-1 K</td>
</tr>
<tr>
<td>X4</td>
<td>X6</td>
<td>9</td>
<td>40</td>
<td>0</td>
<td>20</td>
<td>180</td>
<td>20</td>
<td>0 K</td>
</tr>
<tr>
<td>X4</td>
<td>X7</td>
<td>8</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>80</td>
<td>20</td>
<td>0 K</td>
</tr>
<tr>
<td>X5</td>
<td>X7</td>
<td>5</td>
<td>60</td>
<td>0</td>
<td>20</td>
<td>100</td>
<td>25</td>
<td>0 K</td>
</tr>
<tr>
<td>X6</td>
<td>X7</td>
<td>1</td>
<td>10</td>
<td>7</td>
<td>10</td>
<td>29</td>
<td>30</td>
<td>0 K</td>
</tr>
<tr>
<td>X6</td>
<td>T</td>
<td>2</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>20</td>
<td>29</td>
<td>0 K</td>
</tr>
<tr>
<td>X7</td>
<td>X9</td>
<td>1</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>31</td>
<td>0 K</td>
</tr>
<tr>
<td>X7</td>
<td>T</td>
<td>4</td>
<td>60</td>
<td>0</td>
<td>75</td>
<td>300</td>
<td>30</td>
<td>0 K</td>
</tr>
<tr>
<td>X8</td>
<td>X7</td>
<td>2</td>
<td>20</td>
<td>0</td>
<td>20</td>
<td>40</td>
<td>28</td>
<td>0 K</td>
</tr>
<tr>
<td>X8</td>
<td>X9</td>
<td>3</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>28</td>
<td>31</td>
<td>0 K</td>
</tr>
<tr>
<td>X9</td>
<td>T</td>
<td>3</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>31</td>
<td>0 K</td>
</tr>
<tr>
<td>T</td>
<td>S</td>
<td>-10000</td>
<td>45</td>
<td>25</td>
<td>85</td>
<td>-85000</td>
<td>34</td>
<td>13</td>
</tr>
</tbody>
</table>

**END**

**TOTAL SYSTEM CONTRIBUTION =** 848525

**NO OF BREAKTHRS =** 12, **NO OF NONBREAKTHRS =** 11, **NO OF X CHANGES =** 67

**PAUSE**

**RESERVED TAPE HAS BEEN WRITTEN**
10. Program Messages

One exception to the previous formats is permitted. If the "READY" of "SAVE" card is not the first card in a run this is not considered to be an error, but it is assumed that these are comment cards. The contents of columns 7-72 of all cards in a run (if any) which precede the "READY" or "SAVE" card plus columns 7-72 of the "READY" or "SAVE" card itself are written on the system output device. Thus only columns 1-6 of the "READY" and the "SAVE" card are fixed in format, the rest of the card may be used for comments. The above is also applicable to the "PAUSE" card.

Below is given a list of comments which may be written on the system output device.

Comments 3), 4), 5), 6), 7), 8), 9), 12), and 13), denote errors in data set-up that were caught by the pre-processing routines. Conditions 10) and 11) are considered to be errors only if no "TRANSPORTATION" control card was present. Whenever any of the above error conditions are present, the run is terminated.

Comment 18) is given to convey information but is not regarded as an error.

Comment 17) denotes a trivial infeasibility—in this case the algorithm is not executed.

Comment 2) is written if the algorithm computation was started but not finished. Comment 1) will be present when comment 2) is written.
## OFF LINE PROGRAM COMMENTS

1) **OVERFLOW IN NODE PRICES**  
A node price is greater than 100,000,000. Costs should be rescaled to run job.

2) **RUN TERMINATED AT ARC _____**  
Gives the arc at which run was terminated due to the reason stated above the comment.

3) **RUN TERMINATED DUE TO ERRORS IN THE DATA**  
Self-explanatory

4) **TOO MANY NODES IN THIS RUN**

5) **TOO MANY ARCS IN THIS RUN**

6) **CARD PUNCHING ERROR IN ARC CARD NO. _____**  
These comments are self-explanatory

7) **CARD PUNCHING ERROR IN NODE CARD NO. _____**

8) **THE ARC IN THE ABOVE ALTER CARD IS NOT IN CORE**

9) **SOURCE NODES ARE NOT ADJACENT, ARC _____ _____**  
All arcs having similar first nodes must be adjacent. This comment gives an arc which is separated from another arc having the same first node.

10) **ARC _____ _____ IS A DEAD END ARC**  
The second node of this arc does not appear anywhere as a first node.

11) **NO ARC ENDS AT NODE _____ _____**  
Self-explanatory

12) **CARD _____ NODE _____ NOT IN ARCS**  
A node card appears on which the node is not represented in any arc.

13) **ILLEGAL CONTROL CARD( _____ _____)**  
The control card just read into core is not able to be interpreted by the program.
14) **OUTPUT CONTROL CARD MISSING OR OUR OF SEQUENCE**

15) **RESERVED TAPE HAS BEEN WRITTEN**

16) **NO RESERVED TAPE HAS BEEN WRITTEN**

17) **ARC ___ HAS LOWER BOUND GREATER THAN UPPER BOUND**

18) **NODE ___ NON-CONSERVATIVE, NET FLOW=______**

19) **THIS RUN OUTPUT TO TAPE**

20) **THIS RUN OUTPUT PUNCH**

21) **___ARCS ARE OUT OF KILTER**

---

**Self - explanatory**

This comment states whether an output has been written on a tape other than the system device (as requested by an "OUTPUT TAPE" control card).

**Self-explanatory**

Node has a finite net flow. Negative flow denotes source node.

These comments state where the output to this run may be found.

This run was completed, but there is no feasible solution. As many as 100 arcs are marked with an "N" on the output. "N" denotes that these arcs are not in kilter.
11. Program Operation Notes

The I/O device reference numbers the program uses are given below. Since these numbers vary from installation to installation, they can be changed as indicated in Section 13.

<table>
<thead>
<tr>
<th>I/O Device</th>
<th>Fortran Symbol</th>
<th>Reference Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>System input device-- all control cards and data packages of the &quot;CARDS&quot; variety</td>
<td>KI</td>
<td>5</td>
</tr>
<tr>
<td>System output device-- general editing output and &quot;OUTPUT PRINTER&quot; option</td>
<td>KO</td>
<td>6</td>
</tr>
<tr>
<td>Card punch-- &quot;OUTPUT CARD&quot; output</td>
<td>KQ(1)</td>
<td>7</td>
</tr>
<tr>
<td>Reserved output tape-- &quot;OUTPUT TAPE&quot; output</td>
<td>KQ(2)</td>
<td>3</td>
</tr>
<tr>
<td>Reserved input tape-- data packages of &quot;TAPE&quot; variety</td>
<td>KQ(3)</td>
<td>2</td>
</tr>
</tbody>
</table>

System control cards must be included in the deck whenever the reserved tapes are used. The reference numbers 2 and 3 for the reserved input and output tapes, respectively, were arbitrarily chosen. These numbers can be changed, but they must correspond to the tape numbers specified on the system control cards.

For a reserved output tape the following two control cards must be included:
These cards should immediately precede the data. When the job is run under the ASP system (at the MIT Computation Center), the following card must also be included:

/*SETUP DDNAME=FT03F001,DEVICE=2400-9,ID=(tapeid,RING,SAVE,NL)

This card should immediately follow the job card. Note that "tapeid" is an identification number assigned to the tape by the MIT Computation Center. Three similar control cards must be included whenever a reserved input tape is used, but FT03 should be changed to FT02. The OS/360 user's manual contains more details concerning the use of reserved tapes.

The sequence of operations by the computer when it is doing one problem is as follows:

First the "READY" card is looked for.

Next the data package is read.

Next comes the generation of the output. When outputting is finished, the next run (if any) will be started.

The running time for this program, of course, varies considerably from problem to problem. The input and output time will be roughly proportional to the number of arcs. The execution of the algorithm is the most variable part of the problem, and its duration will depend on the type of problem considered. At the end of "PRINTER" output, the number of
non-breakthroughs that were obtained are written. Also it writes the "number of X changes," which is the sum of the number of arcs in each breakthrough chain, and "number of nodes from which labeling was done," which is the sum of the number of nodes scanned on each labeling operation.

As an example, a problem was run that gave the following statistics:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of arcs</td>
<td>414</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>348</td>
</tr>
<tr>
<td>Number of breakthroughs</td>
<td>40</td>
</tr>
<tr>
<td>Number of non-breakthroughs</td>
<td>179</td>
</tr>
<tr>
<td>Number of X-changes</td>
<td>1915</td>
</tr>
<tr>
<td>Number of nodes from which labeling was done</td>
<td>7550</td>
</tr>
</tbody>
</table>

The upper bounds on the elapsed times were:

<table>
<thead>
<tr>
<th>Description</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Program compilation</td>
<td>2.2 min.</td>
</tr>
<tr>
<td>Data preprocessing</td>
<td>3.3 sec.</td>
</tr>
<tr>
<td>Algorithm computations</td>
<td>3.6 sec.</td>
</tr>
</tbody>
</table>


12. Structure of the Program

A. Main Program

1) Sets up I/O device numbers and dimensions
2) Calls MAINE

B. Subroutine MAINE (with ENTRY OOKMAN for on-line linking and execution)

1) Calls the preprocessing routines
   
   PREDAT
   ARCASY
   MAKEJL
   NODASY
   READER
   TRANSL

2) Calls the subroutine KILTER once for each arc.
3) Calls the postprocessing routine OUTPUT.

The routine also processes certain error and infeasibility conditions.

C. Subroutine PREDAT looks for a control card of the type "READY", "SAVE", or "PAUSE". If it finds a "READY" card, core is cleared and it looks for a control card of the type "CARDS", "TAPE", "SKIP", or "TRANSPORTATION". After it finds a "CARD" or "TAPE" control card, it then looks for the control card "ARCS" on the appropriate input device.

If a "SAVE" card is found the program returns control to the main program and control is passed next to the subroutine READER.

If a "PAUSE" card is found, the end-of-job instructions are executed.

D. Subroutine ARCASY reads arc record after arc record into storage until it comes to a record with "END" or one with "NODES"

The $l_{ij}$, $u_{ij}$, $c_{ij}$, and $x_{ij}$ information is stored in the KL, KU, KC, and KX blocks, respectively. The BCD names of the first nodes are stored in NN, and the BCD names of the second nodes are stored in IJ.

E. Subroutine MAKEJL sets up lists in IL and JL storage. These lists are cumulative counts of the arcs beginning and ending at the nodes. The subroutine also replaces the IJ names by numbers.
P. Subroutine NODASY reads in the node prices, if any.

G. Subroutine READER reads the OUTPUT, ALTER, and COMPUTE control cards.

H. Subroutine TRANSL performs the final operations before going to the Out of Kilter algorithm.

I. Subroutine KILTER tests the arc presented to see if it is in kilter. If it is not in kilter, the assembly language subroutine LABELN is called. Depending on a flag set in LABELN, the KILTER subroutine then calls either UPNOPR or BREAKT. When the arc has been brought into kilter or when it is determined that the arc cannot be brought into kilter, the control passes back to MAINE.

J. Subroutine OUTPUT generates the output required for the run.

K. ASSEMBL routine includes:

1) Assembly language subroutine LABELN performs the labeling operation. If a breakthrough results, the next subroutine called by KILTER will be BREAKT. If a non-breakthrough results, the next subroutine called by KILTER will be UPNOPR.

2) Assembly language subroutine BREAKT alters the quantities of flow in the cycle generated by LABELN.

3) Assembly language subroutine UPNOPR raises the node prices of the labeled nodes by the appropriate amount.

4) Assembly language function NODENO returns the number of the node that has the name presented.

L. ASSEMB2 routine includes:

1) Assembly language function LADDR returns the rightmost 16 bits of the word presented as a 32-bits FORTRAN integer.

2) Assembly language function LDECR returns the leftmost 16 bits of the word presented as a 32-bits FORTRAN integer.

3) Assembly language subroutine PLACE stores the rightmost 16 bits of the first full-word argument in the leftmost 16 bits of the second full-word argument.
13. Compiling the Program

In order to change the I/O device numbers of the program, only the MAIN program need be compiled. The I/O device numbers are the first items to be defined by the program. The symbols assigned to the devices are as follows:

- KI = System input device
- KO = System output device
- KQ(1) = Punch card device
- KQ(2) = Reserved output tape
- KQ(3) = Reserved input tape

In order to change the dimensions of the program, it is necessary to change the dimensions of all the FORTRAN subprograms and also the numeric values of the symbols KQ(4) and KQ(5). The assembly language subprograms need not be changed since they do not contain dimensions information.

Let "a" be the maximum number of arcs allowed in the program and "n" the maximum number of nodes allowed. Then, KQ(4) = a, and KQ(5) = n in the main routine. The storage which must be allocated for each symbol is as follows:
<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>DIMENSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>KL</td>
<td>a</td>
</tr>
<tr>
<td>KC</td>
<td>a</td>
</tr>
<tr>
<td>KU</td>
<td>a</td>
</tr>
<tr>
<td>XX</td>
<td>a</td>
</tr>
<tr>
<td>NL</td>
<td>n</td>
</tr>
<tr>
<td>NN</td>
<td>2n</td>
</tr>
<tr>
<td>NP</td>
<td>n</td>
</tr>
</tbody>
</table>

Must occupy at least \( \{ \)
"a" words of consecutive storage
\( \{ \)
IJ \( n \)
IL \( n + 1 \)
JL \( \max(n + 1, a-2n-1) \)
\( \} \)

JI \( a \)

Total storage for above symbols = \( 5a + 4n + \max(a,3n+2) \)

A total of 108,000 four-byte words were available for dimensions when the program was tested on the IBM 360 model 65 computer. One can choose \( a \) and \( n \) to be any positive integers as long as

\[ 5a + 4n + \max(a,3n+2) \leq \text{full-word storage available for dimensions.} \]
G.3 Out of Kilter Sample Problem

Sub-section 5 of Section G.2 contains a sample problem input listing.

G.4 Out of Kilter Source Listing

The following is a source listing of the Out of Kilter Network Program (included only in MIT library copies).
H.1 QKCORE Discussion

H.1.1 Introduction

As was pointed out in Section 5.2, development of QKCORE, a QuicK in-CORE empirical fuel cost simulator (See Figure H.1) was undertaken to allow completion and evaluation of the nuclear power management model of Figure 2.21. To provide maximum flexibility, QKCORE is programmed as a separate "stand-alone" code suitable for independent fuel management studies.

A pseudo-1D nodal model of LWR reactor core physics is used (See Section H.1.2). Each cycle of a multi-cycle planning horizon may operate in one of three modes:

(1) With reload (i.e., freshly fabricated) enrichment $\epsilon_f$ specified, irradiate to reactivity-limited cycle energy $E_{rc}$. This mode is representative of normal fuel-depletion code operation.

(2) With cycle energy $E_{rc}$ specified, determine reload enrichment $\epsilon_f$ required at start of cycle to generate reactivity-limited $E_{rc}$. This mode is required by SYSOPT.

\[1\] Notation in this Appendix is defined specifically in context rather than in Nomenclature of Appendix I.
Compatibility of the Fuel Cost Simulator

**CORE SIMULATION AND OPTIMIZATION MODEL**

**INITIAL CONDITIONS**
Nuclear fuel cost data

**CORE SIMULATION TO OPTIMIZE NUCLEAR FUEL DESIGNS**

**OPTIMUM RELOAD FUEL:**
- Enrichment
- Batch size
- Min. total cost
- Incremental costs

**SYSTEM OPTIMIZATION MODEL**

**QKCORE SIMULATOR**

**INITIAL CONDITIONS**
Nuclear fuel cost data

**TOTAL NUCLEAR FUEL COST**
- Incremental cost of each reload batch

**SYSTEM OPTIMIZATION MODEL**
(3) If both $\varepsilon_f$ and $E_{rc}$ specified, determine amount of early shutdown or stretchout required. This model represents a compromise where first few cycles of horizon have enrichment fixed and specific cycle energy required.

Total and incremental fuel costs for each cycle are determined on-line as indicated in Section H.1.2.

The limitations of the code are as follows:

(1) modified-scatter refueling with fixed number of zones ($1 < \text{NOZONE} < 10$),

(2) no plutonium recycle,

(3) up to 20 cycles considered,

(4) up to 15 different sets of nuclear generating unit characteristics may be retained simultaneously,

(5) each nuclear unit may have a different set of empirical core physics constants,

(6) up to 5 different sets of empirical fuel constants and

(7) the cost of each operation in the nuclear fuel cycle may be escalated using an input quadratic equation.

H.1.2 Computational Model

The computational model is based on (1) empirical fuel equations (See Table H.1) which represent homogenized unit fuel cell data as a function of fabricated
QKCORE Empirical Fuel Simulator Equations

I. \( k_\infty = K8 = (F_1 + F_2 \varepsilon_f + F_3 \varepsilon_f^2) \)

\[ + (F_4 + F_5 \varepsilon_f + F_6 \varepsilon_f^2) B \]

\[ + (F_7 + F_8 \varepsilon_f + F_9 \varepsilon_f^2) B^2 \]

II. \( KGU = (F_{10} + F_{11} \varepsilon_f + F_{12} \varepsilon_f^2) \)

\[ + (F_{13} + F_{14} \varepsilon_f + F_{15} \varepsilon_f^2) B \]

\[ + (F_{16} + F_{17} \varepsilon_f + F_{18} \varepsilon_f^2) B^2 \]

III. \( \varepsilon = ENRICH = \varepsilon_f . e^{-\alpha_1 B} \)

where

\[ \alpha_1 = (F_{19} + F_{20} \varepsilon_f + F_{21} \varepsilon_f^2) \]

\[ + (F_{22} + F_{23} \varepsilon_f + F_{24} \varepsilon_f^2) B \]

\[ + (F_{25} + F_{26} \varepsilon_f + F_{27} \varepsilon_f^2) B^2 \]

IV. \( KGPU = \alpha_2 (e^{-\alpha_3 B} - e^{-\alpha_4 B}) \)

where

\[ \alpha_2 = (F_{28} + F_{29} \varepsilon_f + F_{30} \varepsilon_f^2) \]

\[ + (F_{31} + F_{32} \varepsilon_f + F_{33} \varepsilon_f^2) B \]

\[ + (F_{34} + F_{35} \varepsilon_f + F_{36} \varepsilon_f^2) B^2 \]

\[ \alpha_3 = F_{37} + F_{38} \varepsilon_f + F_{39} \varepsilon_f^2 \]

\[ \alpha_4 = F_{40} + F_{41} \varepsilon_f + F_{42} \varepsilon_f^2 \]
Table H.1--Continued

\[ V. \sum_a = \text{SIGA} = F_{43} + F_{44} \epsilon_f \]

Units:

- \( F_i = \text{FULCON(I)} \)
- \( \epsilon_f = \) as-fabricated enrichment, w/o U-235
- \( \epsilon = \) current (i.e., at burnup B) enrichment, w/o U-235
- \( B = \) average zone burnup, MWD/kg
- \( KGU = \) uranium inventory, kg U/kg U fab.
- \( KGPU = \) fissile plutonium inventory, kg fissile Pu/kg U fab
- \( \sum_a = \) macroscopic absorption cross section, cm\(^{-1}\)
enrichment $\varepsilon_f$ and current burnup $B$ and (2) empirical reactor equations (See Table H.2) which mockup zone-by-zone irradiation during each cycle.

To facilitate explanation of the model, assume that all the required coefficients in Tables H.1 and H.2 are known a priori. In the first operating mode (See Section H.1.1), the purpose of the model is to answer the following question:

Given the as-fabricated enrichments $\varepsilon_{fi}$ and average zone burnups $B_i$ for non-fresh fuel ($i=2$ to $n$) in an $n$-zone core, what must be the fresh fuel (i.e., $B_1=0$), enrichment $\varepsilon_{f1}$ loaded to give a cycle electrical energy production of $E_c$?

First, the electrical energy production $E_c$ must be converted to thermal energy $\theta_c$. Using a previous assumption (See Section 2.4.2) of constant nuclear incremental efficiency $\eta_{inc}$, Equation (2.52) yields

$$\theta_c = H^o T_{op} + \frac{E_c}{\eta_{inc}}$$  \hspace{1cm} (H.1)

where

$H^o$ = fixed heat consumption rate during operation

$T_{op}$ = time of operation

The next step is the determination of $k_{\infty INNER}$ as an index of the reactivity remaining in the core. Assuming three-zone modified-scatter refueling,
VI. $k_{\text{NEW}} = K8\text{NEW} = 1 + R_1 + R_2\theta c + R_3\theta c^2$

\[ + (R_4 + R_5 \delta k_{\text{INNER}} + R_6\theta c) \delta k_{\text{INNER}} \]

where $\delta k_{\text{INNER}} = k_{\infty_{\text{INNER}}} - 1$

\[ k_{\infty_{\text{INNER}}} = \frac{\sum_{i=2}^{n} (\varepsilon f_i, B_i)}{n-1} \]

VII. $\Phi = \frac{1}{1 + R_7 + R_8\varepsilon f + R_9\varepsilon f^2 + R_{10}\varepsilon f^3 + R_{11} \delta k_{\text{INNER}} + R_{12} \delta k_{\text{INNER}}^2}$

Units:

$R_i = \text{RCRCON}(I)$

$\theta_c = \text{Cycle thermal energy, GWht}$

$n = \text{n-zone core (NOZONE)}$

$\varepsilon f = \text{w/o U-235 as-fabricated}$
Using this index and $\theta_c$ the required energy production, Equation VI of Figure H.2 gives the fresh fuel $k_{\infty}$ needed,

$$k_{\infty}\text{NEW} = k_{\infty}\text{NEW} (\theta_c, k_{\infty}\text{INNER})$$ (H.3)

The fresh ($B_1 = 0$) fuel enrichment is then determined by applying the quadratic equation to

$$k_{\infty}\text{NEW} = k_{\infty}\left(\varepsilon_F^\text{NEW}, 0\right) = F_1 + F_2 \varepsilon_F^\text{NEW} + F_3 \varepsilon_F^2\text{NEW}$$ (H.4)

and solving for $\varepsilon_F^\text{NEW} (\equiv \varepsilon_F^1)$.

Burnup increments for each zone must now be calculated by predicting power-sharing.

Since,

$$\Sigma_f \equiv \left(\frac{\Sigma a}{\nu}\right)\left(\frac{\nu \Sigma F}{\Sigma a}\right) \propto \Sigma a k_{\infty}$$ (H.5)

where $\nu$ = average number of neutrons per fission

$\Sigma_f$ = macroscopic fission cross section, cm$^{-1}$

then

$$\Delta B_i \propto \Sigma_f \propto \left(\Sigma a k_{\infty}\right)_i$$ (H.6)
Since inner zones 2 and 3 see the same flux \( \phi_2 = \phi_3 \), a single fit of outer zone 1 flux \( \phi_1 \) normalized to that of the inner zones suffices to allow a determination of power sharing:

\[
\text{Fraction of Cycle} \quad \text{Energy} \quad \frac{(\mathcal{G} \sum_a k_{\infty})_i}{\phi_1 a_1 k_{\infty 1} + \phi_2 a_2 k_{\infty 2} + \phi_3 a_3 k_{\infty 3}}
\]

where

\[
\mathcal{G}_1 = \frac{1}{(\mathcal{G}_f, \mathcal{G}_B, \mathcal{G}_IN)} \quad \text{of Equation VII}
\]

\[
\mathcal{G}_2 = \mathcal{G}_3 = 1
\]

After the burnup increments are determined for each zone, simulation of one irradiation is complete. Refueling is then represented by discharging zone 3 and renumbering zones 1 and 2 to 2 and 3, respectively. Clearly, the next irradiation can now be simulated by repeating all of the above steps. And so on, for all the cycles of interests. (The other operating cycle modes of Section H.1.1 are easily handled within this framework.)

When all fed and discharged fuel characteristics \( (\mathcal{G}_f, \mathcal{G}_B, \mathcal{G}_IN) \) have been determined, application of the uranium inventory Equation II (See Table H.1), current enrichment Equation III, and fissile plutonium inventory Equation IV provides pertinent mass balance data.
Reload batch fuel cost is then calculated using the simple, straightforward, but approximate equation:

\[
\begin{align*}
\text{Batch Revenue Requirement} \quad &\equiv \left( \frac{\text{Batch Initial Present Valued to Middle of Irradiation}}{\text{Investment Cost}} \right) \left( 1 + y \left( T_{\text{pre}} + \frac{T}{2} \right) \right) \\
&\quad - \left( \frac{\text{Batch Salvage Value}}{1 - y \left( T_{\text{post}} + \frac{T}{2} \right)} \right)
\end{align*}
\]

(H.8)

where \( y = \frac{x}{1 - \tau} \) = average cost of money (before taxes), per year

\( x = \) present value rate, per year

\( \tau = \) income tax rate, fraction of taxable income

\( T = \) total in-core time, years

\( T_{\text{pre}} = \) pre-irradiation lead time for fuel purchases, years

\( T_{\text{post}} = \) post-irradiation lag time for receipt of fuel credit, years

All batches are then present-valued to the study's base date to yield \( T_C^P \), the total nuclear fuel revenue requirement for the "path" \( p \) of cycle energies \( (E_{r1}, E_{r2}, E_{r3}, ...) \) to the horizon. A second path \( p' \), equal to the first in all but one cycle \( (E_{r1}, E_{r2} + \Delta, E_{r3}, ...) \), can also be evaluated. Then, the \( \lambda_{r2} \) incremental cost for that cycle becomes simply

\[
\lambda_{r2} \equiv \frac{\partial T_C^P}{\partial E_{r2}} \approx \frac{T_C^{P'} - T_C^P}{\Delta}
\]

(H.9)
Returning to the question of determining the proper empirical coefficients, data points can be easily generated by a suitable physics-depletion code set such as CELL-CORE (40,41) or even LASER-FLARE (25,50). Multiple regression techniques (15) can be applied directly to the unit fuel cell data with a minimum of pre-fit data handling. On the other hand, the reactor irradiation data is best utilized in terms of the parameters of interest (e.g., power-sharing) as opposed to the physics quantities represented (e.g., flux ratios). In other words, the interpretation of $\Phi$ is qualitatively based on a flux ratio, but the actual $\Phi$ (to be used as input to any data-fitting package) is more appropriately backed-out of the actual power-sharing data using the empirical value of $k_{\infty}$ and $\Sigma_{a_i}$ calculated for the same reactor core conditions.

Sample results for a Zion class 1100 MW PWR are shown in Figure H.2. Coefficients were fitted to Zion data output by CELL-CORE. Cost calculations are all based on annual refuelings with four week outages using unit costs representative of 1975 startup (46).

As an indication (See Table H.3) of simulator accuracy, in attempting to reproduce one of the fitted data points, QKCORE end of cycle burnups were in error by less than 0.6 per cent compared to CORE results (118 out of 19149 MWD/T at the end of second irradiation);
Figure H.2

QKCORE Fuel Simulator Results for 1100 MWe PWR at Steady-State

REACTOR DATA:
3 ZONE MOD-SC.
28.3 TONNE/REF.
\( \eta_{TH} = 32.5\% \)
Table H.3

Comparison of QKCORE versus CORE results for 3.2% U-235 at Steady-state

NOTE: All burnups in MWd/T
30.1 Metric tonnes loaded at each refueling

<table>
<thead>
<tr>
<th></th>
<th>Average Zone Burnup</th>
<th></th>
<th>ERROR: QKCORE vs. CORE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CORE</td>
<td>QKCORE</td>
<td>End of Cycle</td>
</tr>
<tr>
<td></td>
<td>0.0</td>
<td>0.0</td>
<td>Absolute</td>
</tr>
<tr>
<td>Initial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increment</td>
<td>9173</td>
<td>9200</td>
<td></td>
</tr>
<tr>
<td>At End of Cycle 1</td>
<td>9173</td>
<td>9200</td>
<td></td>
</tr>
<tr>
<td>Increment</td>
<td>9976</td>
<td>10067</td>
<td></td>
</tr>
<tr>
<td>At End of Cycle 2</td>
<td>19149</td>
<td>19267</td>
<td>118</td>
</tr>
<tr>
<td>Increment</td>
<td>9294</td>
<td>9163</td>
<td>-13</td>
</tr>
<tr>
<td>At End of Cycle 3</td>
<td>28443</td>
<td>28430</td>
<td>-13</td>
</tr>
</tbody>
</table>

(Discharge)
errors in cycle incremental burnups were higher but still less than 1.5 per cent (131 out of 9294 MWD/T).

Programming the empirical model and its associated cost calculations resulted in the 1300 card Fortran IV program QKCORE which requires 80K bytes of computer memory (plus 26 K for computer supervisor). Less than 0.2 sec of CPU time on an IBM 370 model 155 is required to simulate ten irradiation cycles including costing for each batch.

H.1.3 Code Structure and Mode of Operation

Table H.4 presents a summary of QKCORE subroutines while Figure H.3 portrays the general sequence of operations occurring in a QKCORE production run. (Table H.5 presents information relative to possible error messages printed by subroutine ICERRS.)

In order to calculate incremental costs \( \frac{\partial T_{cr}}{\partial E_{rc}} \), an ELAME table (See Figure H.4) is passed to INCORE. The key path p of cycle energies is evaluated first. Then, each cycle, in turn, (last cycle first) is altered to a p' with a non-key \( E_{rc} \), holding all others constant at their key value. Equation (H.9) is then used to determine \( \lambda_{rc} \) which is then "sandwiched" between the two pertinent cycle energies that differ (See Figure H.4).
## Summary of QKCORE Subroutines

<table>
<thead>
<tr>
<th>Name</th>
<th>Called BY</th>
<th>Calls</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>QKCORE</td>
<td>----------</td>
<td>INCORE</td>
<td>Reads QKCORE input, then calls INCORE (see Table F.3)</td>
</tr>
<tr>
<td>(Main)</td>
<td></td>
<td>ICINPUT</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ICERRS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ERASE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>QKCORE</td>
<td>REDCOR</td>
<td>Supervises in-core simulation;</td>
</tr>
<tr>
<td>(ICINPUT)</td>
<td>(Main)</td>
<td>FULSIM</td>
<td>Has ENTRY ICINPUT to initiate reading of input data by subroutine REDCOR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>INIT3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>EMPRCL</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ICERRS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ICINPUT</td>
<td>INIT2</td>
<td>Reads input data for INCORE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UF6VAL</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SETUUL</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>PVINIT</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>PRTTOP</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>PRTBTM</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ERASE</td>
<td></td>
</tr>
<tr>
<td>FULSIM</td>
<td>INCORE</td>
<td>CONSTS</td>
<td>Supervises fuel irradiation simulation for all E's</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NXTIRR</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>FRSIRR</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSTBAT</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>PRTTOP</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>PRTBTM</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ERASE</td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>Called By</td>
<td>Calls</td>
<td>Purpose</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------</td>
<td>----------------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>CONSTS</td>
<td>FULSIM</td>
<td>UNTCOS, PVPER$</td>
<td>Supervises calculation of unit ($/Kg) cost for all batches</td>
</tr>
<tr>
<td>NXTIRR (FRSIRR)</td>
<td>FULSIM</td>
<td>FK8, FSIGA, FEPF, FK8NEW, FPHI, FECOUT, ICERRS</td>
<td>Performs simulations of next irradiation; Has ENTRY FRSIRR for initial split cycle</td>
</tr>
<tr>
<td>CSTBAT (INIT3)</td>
<td>INCORE, FULSIM</td>
<td>FKGUR, FEPB, FKGPU, UF6VAL, PVPER$, ERASE</td>
<td>Calculates cost of batch of fuel; Has ENTRY INIT3 for initialization</td>
</tr>
<tr>
<td>PRTTOP (PRTBTM)</td>
<td>FULSIM</td>
<td>------</td>
<td>Prints top of FULSIM result table; Has ENTRY PRTBTM to print bottom of table</td>
</tr>
<tr>
<td>Name</td>
<td>Called By</td>
<td>Calls</td>
<td>Purpose</td>
</tr>
<tr>
<td>-----------</td>
<td>------------</td>
<td>-------</td>
<td>---------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>EMPRCL</td>
<td>INCORE</td>
<td>------</td>
<td>Initializes empirical equations; Has multiple ENTRY points for each equation</td>
</tr>
<tr>
<td>(FK8, FKGUR, FEPB, FKGPU, FSIGA, FEPF, FK8NEW, FPHI, FECOUT)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UNTCOS</td>
<td>REDCOR</td>
<td>------</td>
<td>Calculates escalated unit ($/Kg) costs; Has ENTRY INIT2 to initialize escalation constants</td>
</tr>
<tr>
<td>(INIT2)</td>
<td>CONSTS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UF6VAL</td>
<td>REDCOR</td>
<td>PVPERS$</td>
<td>Calculates value of enriched uranium ($/Kg UF₆); Has ENTRY SETUVL to pre-calculate constants in value equation</td>
</tr>
<tr>
<td>(SETUVL)</td>
<td>CSTBAT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P'PER$</td>
<td>REDCOR</td>
<td>------</td>
<td>Calculates present (at base date) value of one dollar; Has ENTRY PVINIT to initialize present value rate; Identical to SYSOPT version (see Appendix F)</td>
</tr>
<tr>
<td>(PVINIT)</td>
<td>CONSTS</td>
<td>CSTBAT</td>
<td></td>
</tr>
<tr>
<td>ICERRS</td>
<td>QKCORE</td>
<td>------</td>
<td>Prints error messages and chooses to terminate execution if severe error occurs (see Table H.2)</td>
</tr>
<tr>
<td>(Main)</td>
<td>INCORE</td>
<td>REDCOR</td>
<td></td>
</tr>
<tr>
<td></td>
<td>REDCOR</td>
<td>NXTIRR</td>
<td></td>
</tr>
<tr>
<td></td>
<td>REDCOR</td>
<td>FRSIRR</td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>Called By</td>
<td>Calls</td>
<td>Purpose</td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
<td>-------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>ERASE</td>
<td>QKCORE (Main)</td>
<td>------</td>
<td>MIT Assembler Language program that sets arrays to zeroes rapidly</td>
</tr>
<tr>
<td></td>
<td>REDCOR</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FULSIM</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CSTBAT</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** Computer installation-dependent dataset reference numbers for RD and WT may be altered in ICNPUT.
Figure H.3

QKCORE Flowchart

INPUT

START

CASE DATA

QKCORE

ENTRY INPUT

UNIT DATA

REDCOR

RETURN

CALCULATIONS & OUTPUT

INCORE

FULSIM

CSTBAT

PRTTOP (PRTBTM)

RETURN

NXTIRR

RETURN
### Table H.5

**QKCORE Error Messages Printed by ICERRS**

<table>
<thead>
<tr>
<th>Number*</th>
<th>Source</th>
<th>Action after Printing</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NXTIRR</td>
<td>RETURN</td>
<td>Cycle energy stretched-out more than 25% of reactivity-limited energy</td>
</tr>
<tr>
<td>2</td>
<td>NXTIRR</td>
<td>RETURN</td>
<td>Cycle energy less than 75% of reactivity-limited energy</td>
</tr>
<tr>
<td>3</td>
<td>QKCORE (MAIN)</td>
<td>Terminate</td>
<td>Input deck has improper sequence and/or card</td>
</tr>
<tr>
<td>4</td>
<td>INCORE</td>
<td>Terminate</td>
<td>Array G in subroutine INCORE too small for problem</td>
</tr>
<tr>
<td>5</td>
<td>INCORE</td>
<td>Terminate</td>
<td>One or more inputs are outside permissible limits</td>
</tr>
<tr>
<td>6</td>
<td>INCORE</td>
<td>RETURN</td>
<td>NCYCTO ≠ NCYCIN + NCYCXS when subroutine INCORE entered</td>
</tr>
<tr>
<td>7</td>
<td>INCORE</td>
<td>Terminate</td>
<td>Data for unit IDNUM not read in</td>
</tr>
<tr>
<td>8</td>
<td>QKCORE</td>
<td>Terminate</td>
<td>&quot;Stop&quot; Card 27 or severe error encountered</td>
</tr>
<tr>
<td>9</td>
<td>REDCOR</td>
<td>RETURN</td>
<td>Power-sharing fractions (see Card 15 of Section H.2) do not sum within $1 \pm 10^{-5}$</td>
</tr>
<tr>
<td>A(=10)</td>
<td>QKCORE</td>
<td>Terminate</td>
<td>Too many cycle-energies being investigated</td>
</tr>
<tr>
<td>B(=11)</td>
<td>NXTIRR</td>
<td>RETURN</td>
<td>Needs reload enrichment &lt; 1.5 w/o U-235 or &gt; 5.0 w/o U-235</td>
</tr>
<tr>
<td>C(=12)</td>
<td>NXTIRR</td>
<td>Terminate</td>
<td>NXTIRR improperly called instead of FRSIRR</td>
</tr>
</tbody>
</table>

*The error number initiating the ICERR print appears as the rightmost digit in the accumulated ERRCOD (which is printed as part of the message).*
**ELAME Table**

<table>
<thead>
<tr>
<th>INDEX I</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_{r1}$</td>
<td>$E_{r2}$</td>
<td>$E_{r3}$</td>
<td>$E_{r4}$</td>
<td>$E_{r5}$</td>
</tr>
<tr>
<td>1</td>
<td>$\lambda_{r1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>$\lambda_{r1}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$E_{r1} + \Delta$</td>
<td>$E_{r3}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>$\lambda_{r1}$</td>
<td></td>
<td>$E_{r3} + \Delta$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>$E_{r1} + 2\Delta$</td>
<td></td>
<td></td>
<td>$E_{r4} + \Delta$</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>$\lambda_{r1}$</td>
<td></td>
<td></td>
<td></td>
<td>$E_{r5} + 3\Delta$</td>
</tr>
<tr>
<td>7</td>
<td>$E_{r1} + 3\Delta$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>$\lambda_{r1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>$E_{r1} + 4\Delta$</td>
<td></td>
<td>$E_{r3} + 4\Delta$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$$C = \text{CYCLE } c$$

$$\text{ELAME } (I, C) = E_{rc} + \left[\frac{(I-1)}{2}\right] \cdot \Delta \quad \text{IF } I \text{ ODD}$$

$$= \lambda_{rc} \quad \text{IF } I \text{ EVEN}$$
H.2 QKCORE Input Specifications

Table H.6 presents the complete input specifications for QKCORE. "INCORE" Card 1 initiates reading of INCORE input data. Card 2 indicates the amount of input data and print options desired. A single set of economic parameters (with quadratic escalation permitted) are input on Cards 3-11. Reactor unit initial conditions and thermal efficiencies appear on Cards 12-15. Card 16-17 contain sets of reactor empirical constants while sets of fuel empirical constants are input on Cards 18-19. "END " Card 20 indicates end of INCORE input. Then, Card 21 "CASE" enters case data on Cards 22-25. Another"CASE" can then be entered, or a "NEW " Card 26 enters any new INCORE data (back to Card 1). Finally a "STOP" Card 27 terminates QKCORE execution.
Table H.6

QKCORE Input Specifications

<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Card 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>1-12</td>
<td>...</td>
<td>&quot;INCORE INPUT&quot; Control Card initiates input of INCORE data</td>
</tr>
<tr>
<td>...</td>
<td>13-80</td>
<td>17A4</td>
<td>Free for comments</td>
</tr>
<tr>
<td><strong>Card 2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NUECON</td>
<td>1-5</td>
<td>I5</td>
<td>Control parameter for new economic data: if: =0 , Cards 3 to 11 not to be read in</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NURCRS</td>
<td>6-10</td>
<td>I5</td>
<td>Number of individual reactors (i.e., nuclear units) for which data to be read in, 0 ≤ NURCRS ≤ MXRCRS (=15)</td>
</tr>
<tr>
<td>NURCRK</td>
<td>11-15</td>
<td>I5</td>
<td>Number of sets of reactor empirical constants for which data to be read in, 0 ≤ NURCRK ≤ MXRCRK (=15)</td>
</tr>
<tr>
<td>NUFULK</td>
<td>16-20</td>
<td>I5</td>
<td>Number of sets of fuel empirical constants for which data to be read in, 0 ≤ NUFULK ≤ MXFULK (=5)</td>
</tr>
<tr>
<td>RELCST</td>
<td>21</td>
<td>L1</td>
<td>Print option for relative cost results (TCP' - TCP) in ELAME table, F = No, T = Yes</td>
</tr>
<tr>
<td>INCCST</td>
<td>22</td>
<td>L1</td>
<td>Print option for incremental cost results in ELAME table, F = No, T = Yes</td>
</tr>
</tbody>
</table>
### Table H.6—Continued

<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
</table>
| BALCST    | 23      | L1     | Print option for batch costs of key cycle energy path \( p \)  
|           |         |        | \( F = \text{No} \)  
|           |         |        | \( T = \text{Yes} \)  
| NBLCST    | 24      | L1     | Print option for batch costs at all cycle energy paths \( p' \)  
|           |         |        | \( F = \text{No} \)  
|           |         |        | \( T = \text{Yes} \)  
| PIRDAT    | 25      | L1     | Print option for irradiation data of all paths,  
|           |         |        | \( F = \text{No} \)  
|           |         |        | \( T = \text{Yes} \)  
| PBATCS    | 26      | L1     | Print option for detailed batch cost data of all paths,  
|           |         |        | \( F = \text{No} \)  
|           |         |        | \( T = \text{Yes} \)  

**Note:** Cards 3 to 11 may be omitted from subsequent INCORE INPUT blocks if no changes in previous economic data read in. Then, NUECON = 0. If QKCORE used in SYSOPT overlay structure (See Section F.1.2), always use NUECON = 1.

**Card 3**

| ECTITL    | 1-80    | 20A4   | Title for economic data |

**Card 4**

| XF        | 1-10    | F10.3  | Enrichment of diffusion plant feed material (yellowcake), weight fraction U-235 |
| XW        | 11-20   | F10.3  | Enrichment of diffusion plant tails, weight fraction U-235 |
| TXRATE    | 21-30   | F10.3  | \( \gamma \), income tax rate, fraction of taxable income |
Table H.6--Continued

<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVRATE</td>
<td>31-40</td>
<td>F10.3</td>
<td>x, present value rate, fraction per year</td>
</tr>
<tr>
<td>TBASE</td>
<td>41-50</td>
<td>F10.3</td>
<td>Calendar base data for present valuing, years</td>
</tr>
<tr>
<td>DTPRE</td>
<td>51-60</td>
<td>F10.3</td>
<td>(T_{pre}), pre-irradiation lead time for fuel purchases, years</td>
</tr>
<tr>
<td>DTPST</td>
<td>61-70</td>
<td>F10.3</td>
<td>(T_{pst}), post-irradiation lag time for receipt of fuel credit, years</td>
</tr>
<tr>
<td>DTY2F6</td>
<td>71-80</td>
<td>F10.3</td>
<td>Effective delay time from yellowcake to (\text{UF}_6), years</td>
</tr>
</tbody>
</table>

**Card 5**

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A0(1)</td>
<td>1-10</td>
<td>F10.3</td>
<td>Constant term in yellowcake unit cost escalation, $/lb \text{U}_3\text{O}_8</td>
</tr>
<tr>
<td>A1(1)</td>
<td>11-20</td>
<td>F10.3</td>
<td>Linear coefficient in yellowcake unit cost escalation, $/lb \text{U}_3\text{O}_8/\text{year}</td>
</tr>
<tr>
<td>A2(1)</td>
<td>21-30</td>
<td>F10.3</td>
<td>Quadratic coefficient in yellowcake unit cost escalation, $/lb \text{U}_3\text{O}_8/\text{year}^2</td>
</tr>
</tbody>
</table>

**Card 6**

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A0(2)</td>
<td>1-10</td>
<td>F10.3</td>
<td>Constant term in uranium conversion unit cost escalation, $/kg\text{U}</td>
</tr>
<tr>
<td>A1(2)</td>
<td>11-20</td>
<td>F10.3</td>
<td>Linear coefficient, $/kg\text{U}/\text{year}</td>
</tr>
<tr>
<td>A2(2)</td>
<td>21-30</td>
<td>F10.3</td>
<td>Quadratic coefficient, $/kg\text{U}/\text{year}^2</td>
</tr>
<tr>
<td>FCOR</td>
<td>31-40</td>
<td>F10.3</td>
<td>Yield in uranium conversion step, fraction</td>
</tr>
<tr>
<td>Variable</td>
<td>Columns</td>
<td>Format</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>---------</td>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>A0(3)</td>
<td>1-10</td>
<td>F10.3</td>
<td>Constant term in separative work unit cost escalation, $/kg SWU</td>
</tr>
<tr>
<td>A1(3)</td>
<td>11-20</td>
<td>F10.3</td>
<td>Linear coefficient, $/kg SWU/year</td>
</tr>
<tr>
<td>A2(3)</td>
<td>21-30</td>
<td>F10.3</td>
<td>Quadratic coefficient, $/kg SWU/year²</td>
</tr>
<tr>
<td>Card 8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A0(4)</td>
<td>1-10</td>
<td>F10.3</td>
<td>Constant term in fabrication unit cost escalation, $/kg Fab.</td>
</tr>
<tr>
<td>A1(4)</td>
<td>11-20</td>
<td>F10.3</td>
<td>Linear coefficient, $/kg Fab./year</td>
</tr>
<tr>
<td>A2(4)</td>
<td>21-30</td>
<td>F10.3</td>
<td>Quadratic coefficient, $/kg Fab./year²</td>
</tr>
<tr>
<td>FFAB</td>
<td>31-40</td>
<td>F10.3</td>
<td>Yield in fabrication step, fraction</td>
</tr>
<tr>
<td>Card 9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A0(5)</td>
<td>1-10</td>
<td>F10.3</td>
<td>Constant term in shipping and reprocessing unit cost escalation, $/kg S&amp;R (U+Pu)</td>
</tr>
<tr>
<td>A1(5)</td>
<td>11-20</td>
<td>F10.3</td>
<td>Linear Coefficient, $/kg S&amp;R (U+Pu)/year</td>
</tr>
<tr>
<td>A2(5)</td>
<td>21-30</td>
<td>F10.3</td>
<td>Quadratic Coefficient, $/kg S&amp;R(U+Pu)/year²</td>
</tr>
<tr>
<td>FSAR</td>
<td>31-40</td>
<td>F10.3</td>
<td>Yield in reprocessing step, fraction</td>
</tr>
<tr>
<td>Card 10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A0(6)</td>
<td>1-10</td>
<td>F10.3</td>
<td>Constant term in uranium reconversion unit cost escalation, $/kg U.</td>
</tr>
<tr>
<td>A1(6)</td>
<td>11-20</td>
<td>F10.3</td>
<td>Linear coefficient, $/kg U/year</td>
</tr>
<tr>
<td>Variable</td>
<td>Columns</td>
<td>Format</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>---------</td>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>A2(6)</td>
<td>21-30</td>
<td>F10.3</td>
<td>Quadratic coefficient, $/\text{kg U/year}^2$</td>
</tr>
<tr>
<td>FCRE</td>
<td>31-40</td>
<td>F10.3</td>
<td>Yield in uranium reconversion step, fraction</td>
</tr>
<tr>
<td>A0(7)</td>
<td>1-10</td>
<td>F10.3</td>
<td>Constant term in fissile plutonium value escalation, $/\text{gm fis. Pu}$</td>
</tr>
<tr>
<td>A1(7)</td>
<td>11-20</td>
<td>F10.3</td>
<td>Linear Coefficient, $/\text{gm fis. Pu/year}$</td>
</tr>
<tr>
<td>A2(7)</td>
<td>21-30</td>
<td>F10.3</td>
<td>Quadratic coefficient, $/\text{gm fis. Pu/year}^2$</td>
</tr>
</tbody>
</table>

**Card 11**

Note: There must be NURCRS sets of Cards 12 to 15, one for each nuclear unit. If no change in previous NURCRS (nuclear unit data read in previously), NURCRS may equal zero. However, if QKCORE used in SYSOPT overlay structure (See Section F.1.2), always use NURCRS > 0

<table>
<thead>
<tr>
<th>Card 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDNO</td>
</tr>
<tr>
<td>NAME</td>
</tr>
<tr>
<td>MWCAP</td>
</tr>
<tr>
<td>IRCRKA</td>
</tr>
<tr>
<td>IFULKA</td>
</tr>
<tr>
<td>NOZONE</td>
</tr>
<tr>
<td>ZONKG</td>
</tr>
</tbody>
</table>
Table H.6--Continued

<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFFNET</td>
<td>41-50</td>
<td>F10.2</td>
<td>Average net thermal efficiency for unit fraction</td>
</tr>
<tr>
<td>DECRIT</td>
<td>51-60</td>
<td>F10.2</td>
<td>Energy remaining in split cycle (at start of simulation) until reactivity-limited burnup reached, GWHe</td>
</tr>
<tr>
<td>DESTCH</td>
<td>61-70</td>
<td>F10.2</td>
<td>Maximum stretchout permitted in cycle with fixed reload enrichment, GWHe</td>
</tr>
<tr>
<td>EFFINC</td>
<td>71-80</td>
<td>F10.2</td>
<td>Incremental net thermal efficiency for unit fraction</td>
</tr>
</tbody>
</table>

If = 0 or blank, EFFINC set equal to EFFNET internally.

Card 13

<table>
<thead>
<tr>
<th>N</th>
<th>1-2</th>
<th>12</th>
<th>Number of entries to follow for EPFFX 0&lt;(N&lt;)MXYTO (=20) - NCYXS</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPFFX(1)</td>
<td>3-80</td>
<td>F8.3,</td>
<td>Refueling enrichment already ordered for reactor, w/o U-235</td>
</tr>
<tr>
<td></td>
<td>7F10.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

if < 0, \(|\epsilon_f|\) is enrichment loaded at that refueling with reactivity-limited energy to be determined.

if =0 (or blank), enrichment not ordered; free to choose reload enrichment to give reactivity-limited energy desired.

if > 0, \(\epsilon_f\) enrichment ordered, extract cycle energy (regardless of reactivity-limited energy).

Note: If N > 8, there must be \([(N-1)/8]\) Card 14's for remaining EPFFX
### Table H.6--Continued

<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Card 14</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPFFX(9)</td>
<td>1-80</td>
<td>8F10.3</td>
<td>Remaining EPFFX (see Card 13)</td>
</tr>
<tr>
<td></td>
<td>to EPFFX(N)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Note:</strong></td>
<td></td>
<td></td>
<td>There must be NOZONE Card 15, one for each zone of the reactor. First Card 15 is for Zone 1 (freshest fuel), while last Card 15 is for Zone NOZONE (about to be discharged).</td>
</tr>
<tr>
<td><strong>Card 15</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPFSRT</td>
<td>1-10</td>
<td>F10.3</td>
<td>$\varepsilon_f^*$, As-fabricated enrichment w/o U-235</td>
</tr>
<tr>
<td>BSRT</td>
<td>11-20</td>
<td>F10.3</td>
<td>$B_i$ Current average burnup at start of simulation, MWD/kg U fab.</td>
</tr>
<tr>
<td>FABINV</td>
<td>21-30</td>
<td>F10.3</td>
<td>Remaining book value of fabrication to be depreciated before discharge, $/kg U fab.</td>
</tr>
<tr>
<td>SRCINV</td>
<td>31-40</td>
<td>F10.3</td>
<td>Current book value of shipping, reprocessing and reconversion (to be appreciated before discharge), $/kg (U+Pu) disch.</td>
</tr>
<tr>
<td>POWFRC</td>
<td>41-50</td>
<td>F10.3</td>
<td>Power-sharing for this zone during this initial split cycle, fraction of total core output</td>
</tr>
</tbody>
</table>

$$\sum_{i=1}^{\text{NOZONE}} \text{POWFRC}_i - 1 \text{ must be } < 10^{-5}$$

**Note:** If simulation does not start with split cycle, zone parameters for last Card 15 should be chosen judiciously since instantaneous depreciation of FABINV and appreciation of SRCINV can result in error in total cost (incremental costs are not affected). (Subroutine CSTBAT currently assumes the initial cycle is a split cycle.) Try EPFSRT = 1.0, FABINV = 0.0 and SRCINV = AO(5) + AO(6) to net error to zero.
Table H.6--Continued

<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Note:</strong></td>
<td></td>
<td></td>
<td>There must be NURCRK sets of Cards 16 and 17, one set for each set of reactor empirical constants. If no change in NURCRK sets of constants read in previously, NURCRK may equal zero. However, if QKCORE used in SYSOPT overlay structure (see Section F.1.2), always use NURCRK &gt; 0.</td>
</tr>
</tbody>
</table>

**Card 16**

RCRKTL 1-80 20A4 Title card for set of reactor empirical constants

**Note:** There must be three Card 17's to accommodate the 18 constants in each set.

**Card 17**

RCRCON(1) 1-80 3(6E12.6) R_k, Reactor empirical constants, 12 constants currently used (see Table H.1)

**Note:** There must be NUFULK sets of Cards 18 and 19, one set for each set of fuel empirical constants. If no change in NUFULK sets of constants read in previously, NUFULK may equal zero. However, if QKCORE used in SYSOPT overlay structure (see Section F.1.2), always use NUFULK > 0.

**Card 18**

FULKTL 1-80 20A4 Title card for set of fuel empirical constants

**Note:** There must be eight Card 19's to accommodate the 48 constants in each set.

**Card 19**

FULCON(1) 1-80 8(6E12.6) F_i, Fuel empirical constants, 44 currently used (see Table H.1)

**Card 20**

... 1-4 ... "END " Control card signifying end of REDCOR input.
Table H.6--Continued

<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
<td>5-80</td>
<td>19A4</td>
<td>Free for comments</td>
</tr>
</tbody>
</table>

**Card 21**

| ... | 1-4 | .. | "CASE" Control card indicating case data to be read by QKCORE |
| ... | 5-80 | 19A4 | Free for comments |

**Card 22**

| CATITL | 1-80 | 20A4 | Case title card |

**Card 23**

| NCYCIN | 1-10 | I10 | Number of cycles involved in horizon (initial cycle assumed split and final cycle may be split) |
| NCYCXS | 11-20 | I10 | Number of complete extra (excess) cycles beyond horizon (=NOZONE-1) |

**Note:** \( \text{NCYCTO} = \text{NCYCIN} + \text{NCYCXS} \leq \text{MXCYTO} (=20) \)

| IDNUM | 27-30 | 6X,14 | IDNO of unit being input (used to retrieve unit data input by REDCOR) |
| ECHDOV | 31-40 | F10.2 | Energy held over beyond horizon in split cycle, \( 0 \leq \text{ECHDOV}, \text{GWHe} \) |

**Note:** There must be NCYCTO sets of Card 24 and 25, one set for each cycle in simulation.

**Card 24**

| I | 1-10 | I10 | Cycle number, \( 1 \leq I \leq \text{NCYCTO} \) |
| NECBAL | 11-20 | I10 | Position of key cycle energy on Card 25, \( 1 \leq \text{NECBAL} \leq \text{NES} \) |
| TS | 21-30 | F10.4 | Calendar time at start of irradiation cycle, years |
| TE | 31-40 | F10.4 | Calendar time at end of irradiation cycle, years |
### Table H.6—Continued

<table>
<thead>
<tr>
<th>Variable</th>
<th>Columns</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NES</td>
<td>41-50</td>
<td>I10</td>
<td>Number of cycle energies to be read in on Card 25, $1 \leq NES \leq \lfloor MXESX2+1/2 \rfloor = 25$</td>
</tr>
<tr>
<td>TO</td>
<td>51-60</td>
<td>F10.4</td>
<td>Length of time unit operated during cycle, years $\leq TE-TS$</td>
</tr>
</tbody>
</table>

**Note:** There must be $\lfloor (NES + 7)/8 \rfloor$ of Card 25 to accommodate the NES cycle energies.

#### Card 25

| ERC(1)   | 1-80   | 8F10.4 | Alternative cycle energies for cycle I, GWHe [If I=1 and not split cycle, ERC(1) = 0.03] |

**Note:** Next card may be "NEW" Card 26, "CASE" Card 21 or "STOP" Card 27 with input sequence reverting to appropriate point.

#### Card 26

| ...      | 1-4    | ...    | "NEW" "Control card initiates input of new INCORE data. Revert to Card 1 in input sequence. |
| ...      | 5-80   | 19A4   | Free for comments |

#### Card 27

| ...      | 1-4    | ...    | "STOP" Control card to terminate execution of QKCORE for this computer run. |
| ...      | 5-80   | 19A4   | Free for comments |
H.3 QKCORE Sample Problem

Figure H.5 presents a QKCORE Sample Problem input deck which is, in fact, part of (i.e., Reactor 2) the SYSOPT Sample Problem in Figure F.4. Figure H.6 presents a summary of QKCORE output for the Sample Problem.
FIGURE H.5

QKCORE
SAMPLE PROBLEM INPUT DECK

// DEATON //CLASS=H //REGION= \ # //MAIN_LINE=26 //CAUS=30 //TIME=\ 0
//SHE //CALC0 //CALC= //PROP= //USE= //FIL= //M789 //6943 //LOAD //QKCORE (GO)

INCOME INPUT

1 1 2 22222

TYPICAL SET OF ECONOMIC DATA \#F: MH(22.27 NOTES) & EM (MN 27/11)
0.0711 .902 .90 .97 0.6 0.329 .60 0.123 .
8.00 .97 .
9.00 1.21 1.21 1.21 1.21 .
20.70 .97 .
45.00 .97 .
3.00 .97 .
7.50 .
200 NK-2 1050 1 1 3 28300. .316 700. 500.
1 3.4 3 4 4 48.80 12.00 .3282 
3.2 14.0 24.40 9.00 .3519 
3.2 28.0 26.8 9.00 .3199 
REACTOR DATA FOR 1.00 MWE ZICN CLASS; 3 ZONE; NO PU RECYCLE COMPUTER VERS.
.141076 .090021486 .3435/4E-09 1.70111 -17.7720 .000105261 KNG
5.69086 -4.58587 2 0.141076 .090021486 .3435/4E-09 1.70111 -17.7720 .000105261 KNG

REACTOR DATA FOR 1.00 MWE ZICN CLASS; 3 ZONE; NO PU RECYCLE SLIDE RULE VERS.
.20943 .00017424 .28845 KNG
2.587087 -1.665217 1.18269 0.0 4.34783 0.0 PHI

FUEL DATA FOR 1.00 MWE ZICN CLASS; 3 ZONE; NO PU RECYCLE COMPUTER VERS.
.805642E 00 1.95099E 00 1.5351E-01 -1.46402E-01 1.02497E-02 -1.97056E-03A1AX2 KB
.26350E-01 .17222E-01 1.00 .
A3K6 A1U
-1.9054E-02 .21709E-03 1.3339E-06 1.8037E-07 .17205E-07 .17205E-07 A1A2K6
A3K6 A1U
.11455E 00 3.15555E 01 -1.26230E-02 -1.94474E-03 1.80791E-03 .10522E-03A1A2K6 A1A2
.31190E-04 4.1716E-04 1.5600E-02 3.2231E-02 .213157E-02 -1.57757E-04A1A2
A3K6 A1U
-.39455E-04 4.3105E-04 1.3552E-02 1.6567E-05 1.2596E-05 1.2596E-05A1A2K6 A1A2
A3K6 A1U
.112495E-02 2.6937E-03 .29034E-04 1.52005E-04 .270667E-04 .270667E-04 A1A2
A3K6 A1U
.53238 .01760
FUEL DATA FOR 1.00 MWE ZICN CLASS; 3 ZONE; NO PU RECYCLE SLIDE RULE VERS.
.955 .090 
.00097 1.00 .
A1A2 K6 A3K6 A1U
.00137 .00108 .00 .E-06 .
A1A2 W0 A2K6 A1U
.0652 .00365 .00156 .
A1A2 W0 A2K6 A1U
.00071 .00071 .
A1A2 W0 A2K6 A1U
.0532 .00872 .
A1A2 W0 A2K6 A1U

END OF INCOME INPUT

CASE

REACTOR 2 UNDER STRATEGY 2 AT A FEW REPRESENTATIVE CYCLE ENERGIES
0.00 1.00 3.00 5.00 7.00 9.00 11.00 13.00 15.00 17.00 19.00 21.00 23.00 25.00 27.00

STOP /*
Figure H.6

QKCORE Sample Problem Output

INDEX 1 IDND 200  
** ** ** ** INCREMENTAL REACTOR TOTAL COST (PV$/MWHE) ** ** **

REACTOR TOTAL COST FOR BALANCED EC'S (ECBAL) = 52762.571 10**3PV$

<table>
<thead>
<tr>
<th>CYCLE</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>ECBAL</th>
<th>700.0</th>
<th>7700.0</th>
<th>7500.0</th>
<th>7500.0</th>
<th>7700.0</th>
<th>7500.0</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>CYCLE</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>EL</th>
<th>500.0</th>
<th>7200.0</th>
<th>7400.0</th>
<th>7500.0</th>
<th>7700.0</th>
<th>7500.0</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>INLST</th>
<th>0.0354***</th>
<th>1.6805***</th>
</tr>
</thead>
<tbody>
<tr>
<td>STL.</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>STL.</td>
<td>0.0618</td>
<td>0.0000</td>
</tr>
<tr>
<td>STL.</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>STL.</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>
H.4 QKCORE Source Listing

The following is a Fortran IV source listing of the QKCORE code (included only in MIT library copies).
### APPENDIX I
#### NOMENCLATURE AND ACRONYMS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Dimension&lt;sup&gt;1&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area under fractional load-duration curve</td>
<td>MW</td>
</tr>
<tr>
<td>a</td>
<td>Coefficient of cycle energy in linear approximation to ( \lambda )</td>
<td>( \frac{$}{(\text{MWH})^2} )</td>
</tr>
<tr>
<td>AH</td>
<td>Available Hours, those during which a unit is available (7)</td>
<td>hours</td>
</tr>
<tr>
<td>b</td>
<td>Constant term in linear approximation to ( \lambda )</td>
<td>( \frac{$}{\text{MWH}} )</td>
</tr>
<tr>
<td>C</td>
<td>(See Subscripts)</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>Numerical constant</td>
<td></td>
</tr>
<tr>
<td>CORSOM</td>
<td>CORS&lt;sup&gt;Re&lt;/sup&gt; Simulation and Optimization Model</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Customer electric energy demand</td>
<td>MWH</td>
</tr>
<tr>
<td>d</td>
<td>Duration of load, amount of time that load ( \geq ) specified power level</td>
<td>hours</td>
</tr>
<tr>
<td>DM</td>
<td>Equivalent load spacing along ( F ) curves</td>
<td>MW</td>
</tr>
<tr>
<td>E</td>
<td>Electric energy produced</td>
<td>MWH</td>
</tr>
<tr>
<td>( \mathcal{E} )</td>
<td>Set of all ( E_{\text{rcp}} ) or {E_{\text{rcp}} }</td>
<td>MWH</td>
</tr>
<tr>
<td>e</td>
<td>Electric energy unit cost</td>
<td>( \frac{\text{mills}}{\text{MWH}} \equiv \frac{\text{kwhe}}{\text{MWH}} )</td>
</tr>
<tr>
<td>F</td>
<td>Fractional load-duration, probability that load ( \geq ) specified power level ( ) at random instant</td>
<td>fraction of period</td>
</tr>
</tbody>
</table>

<sup>1</sup>The symbol \( \$ \) represents present-valued or discounted dollars while \( |\$| \) represents absolute-value or non-discounted dollars. All MW are in net megawatts electric.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_G )</td>
<td>Probability density function of unit performing (capable of ( P_G ) MW)</td>
</tr>
<tr>
<td>( f_0 )</td>
<td>Probability density function of unit not performing (derated ( P_0 ) MW)</td>
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<tr>
<td>( f )</td>
<td>Forced-outage importance, fraction of FOH actually affecting system generating operations</td>
</tr>
<tr>
<td>FOH</td>
<td>Forced-Outage Hours, those during which a unit was unavailable due to a forced-outage (7)</td>
</tr>
<tr>
<td>FOR</td>
<td>Forced-Outage Rate (7), See Equation (2.6)</td>
</tr>
<tr>
<td>FORH</td>
<td>Forced-Outage Reserve Hours, those during which a unit was unavailable due to a forced-outage, but would have been in reserve shutdown status if available.</td>
</tr>
<tr>
<td>FOSH</td>
<td>Forced-Outage Service Hours, those during which a unit was unavailable due to a forced-outage, but would have been in service status if available</td>
</tr>
<tr>
<td>( g )</td>
<td>(See Subscripts)</td>
</tr>
<tr>
<td>H</td>
<td>Heat input rate</td>
</tr>
<tr>
<td>h</td>
<td>Heat rate</td>
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<tr>
<td>I</td>
<td>(See Subscripts)</td>
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<tr>
<td>K</td>
<td>Unit capacity</td>
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<td>k</td>
<td>Unit capacity above minimum</td>
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<tr>
<td>L</td>
<td>Capacity factor</td>
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<tr>
<th>Dimension</th>
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Subscripts

ACT  ACTual
C    Cycle number at end of planning horizon
c    Cycle or contract
D    Direct demand
e    Equivalent or expected
EST  ESTimated
F    Fossil
G    Generating mode
g    Ordered sub-group of unit increments
H    Hydro
I    Indirect demand
I    Total number of capacity increments for unit
\ell Total number of capacity increments currently being considered for unit
i    Increment of unit capacity
inc  incremental
N    Nuclear
O    Outage
P    Pumped-hydro or pumping mode
P    Period number
R    Number of reactors or generating units
R'   Number of on-line reactors
r    Reactor or generating unit
REJ  REJection level
S    Startup-shutdown
Subscripts

T  Total for utility system
U  Unserved (energy), urgent or emergency (purchases)
Z  Total number of periods in planning horizon
Z+1 Fictitious holdover period beyond planning horizon
Superscripts

max  maximum
min  minimum
o    Out, as in without
s    Shape iteration
t    Trial or inner total cost iteration
w    With
wo   without
——   Average; levelized
*    At the optimum
•    At the acceptable optimum
°    At zero; is invariant
'    Availability-based
APPENDIX J

REFERENCES

(1) "AEC to Raise Enrichment Prices in August and Institute an Annual 2% Hike," Nucleonics Week, 14, 7, February 15, 1973.


Bennett, L. L. and J. Turnage of ORNL, personal communication, October 12, 1972.


(36) Jenkins, R. T., of TVA, personal communication, September 1970.


(44) Koncel, E. F., to M. Benedict, personal communication, October 11, 1972.


BIOGRAPHY OF Paul F. Deaton

PERSONAL INFORMATION

Birth date: June 22, 1944  5' 8"; 170 pounds
Married; Two children  Health: excellent

VOCATIONAL OBJECTIVE: Employment in the area of nuclear economics and system analysis, particularly in power management, fuel management or fuel cycle analysis.

EDUCATION

Massachusetts Institute of Technology, Cambridge, Massachusetts
Currently completing PhD thesis in the Department of Nuclear Engineering: "A System Integration and Optimization Model for Nuclear Power Management", Adviser: Professor E.A. Mason. Working closely with large Midwest utility sponsoring the research, thesis involves application of operations research methods to simulate and optimize their electric generating system which possesses both fossil and nuclear power plants. Graduate courses include nuclear physics, reactor engineering, reactor physics, nuclear chemical engineering, economics of nuclear power and space applications of nuclear energy. Minor includes managerial accounting, financial management and economics of fuel and power.

Cumulative grade average: 5.0 (5.0 = A)
Expected degree and date: PhD; January 1973
Member: American Nuclear Society; President, Westgate Community Association (Married students in MIT housing).

University of Cincinnati, Cincinnati, Ohio
Majored in Chemical Engineering. Courses included process economics and control, physical and chemical rate processes, material and energy balances, organic and physical chemistry, and modern physics.

Rank in class: 1st in 223
Cumulative grade average: 3.91 (4.0 = A)
Degree and date: B.S.Ch.E. (with High Honors); June 1967
Four scholarships
Member: American Institute of Chemical Engineers, Varsity Baseball
Honorary: Vice-president, Tau Beta Pi; Omicron Delta Kappa; Phi Eta Sigma; Phi Lambda Upsilon.

WORK EXPERIENCE

Summer work in Nuclear Division's new fuel management group
adapting computer codes to in-house IBM/360 computer.
Familiar with: 2DB, ANISN, FLARE, CELL-MOVE, GGC-3, CINCAS
and COBRA. Programming capabilities include Fortran II,
Fortran IV, BASIC, MAD, Assembler and Job Control languages.

Raphael Katzen Associates, Cincinnati, Ohio (1967): Part-time
work during senior year of college, organizing the data-files
and design notebooks of this chemical engineering consulting
firm.

Co-operative work experience included 10 months in engineering
department as draftsman and checker, 7 months as metallurgical
laboratory technician using classical methods of analysis, and
7 months as a technician in an industrial demonstration labora-
tory.

PUBLICATIONS

"A System Integration and Optimization Model for Nuclear Power

"Parallel Derivation of Marginal Costs Pertinent to Utility

MILITARY STATUS: First Lieutenant in U.S. Army Reserves with
3-year Ready Reserve obligation remaining.

BACKGROUND AND INTERESTS: Born and raised in small Ohio town;
active in sports; hobbies include bridge, chess and flying.
C******************************************************
C*       SYINT      :  AN ELECTRIC UTILITY SYSTEM INTEGRATION MODEL *
C*               WRITTEN BY PAUL F. DEATON *
C*                          M.I.T. DOCTORAL THESIS, MARCH 1973 *
C*                                                     *
C******************************************************
C MAIN PROGRAM
C SYSINT VERSION 1-01-73
COMMON/INTEGR/RD,WT
INTEGER RD,WT
CALL STRTIM
WRITE(WT,900)
CALL SUPSIM
STOP

900 FORMAT(T31,72('*)/T31,**',T102,**'/T31,**',T37,'SYINT:
$ AN ELECTRIC UTILITY SYSTEM INTEGRATION MODEL',T102,**'/
$T31,**',T64,'WRITTEN BY PAUL F. DEATON',T102,**'/
$T31,**',T58,'M.I.T. DOCTORAL THESIS, MARCH 1973',T102,**'/
$T31,**',T102,**'/T31,72('*)'/T56,'VERSION 1-01-73')
END

BLCK DATA
C SYSINT VERSION 10-15-71
C INITIALIZES CONSTANT DATA IN COMMON AREAS
C ******************************************************
C IMPLICIT REAL*8 (A-H,O-$)
C COMMON VARIABLES
C VARIABLES DIMENSIONED IN MULTIPLES OF MAXPLT, MAX NO. OF STATIONS
COMMON/PLTDAT/IDNO(100),NAME(100),TYPE(100),SUSDHT(100),PNCM(100),
$NPTS(100),MWPT(5,100),HTRAT(5,100)
COMMON/PERDAT/AVLBTY(100),CSTBTU(100),STATUS(100),EXPHRS(100),
$EXPBTU(100),EXPWH(100),NORDER(500),COST(100),ENERGY(100),
$SUPCST(100),MRGCST(5,100)
C OTHER VARIABLES COMMON TO SEVERAL SUBROUTINES
COMMON/PROB/DM,DT,GWHER,DAYS,IEMIN,IEMAX,PEMIN,PEMAX,PROB(500)
COMMON/FLOAT/EPS,TRACE,PKMW,SPNRES,CSTEMR
COMMON/TITLE/SGTITLE(10),PDITLE(10)
COMMON/INTEGER/RD,WT,PUNCH,CARD,TAPE,ERRCOD,NOSTNS,NPER,NPERS,NPERI
$,IDSTRG,PHMIN,PHMAX,MBRNUM
COMMON/LDINFO/LDTYPE,LDTYPES,LOAD(50,25),NORDOP,NOENTRY,NOBASE,
$NOPEAK,NNORD
COMMON/MAXIMUM/IDIMAX,MAXPLT,MAXPER,MAXNPT
COMMON/CONSTS/ZERO,ONE,TWO,HALF,TENT,TENTH,HUNDRD,CENTI,THOUS,MILLI
COMMON/LOGICAL/MINI,MIDI,MAXI,NPM,PCHING
COMMON/SUSD/S(20)
COMMON/MAINT/MAINT(100,20)
C MAINT IS DIMENSIONED (MAXPLT,MAXPER/5) THE 5 IS 511/INTEGER*2
COMMON/MURGER/CTEMP500),NEWCOD(5),NEWCST(5),MPTS,IFIRST,ILAST
C NEWCST & NEWCOD ARE DIMENSIONED MAXNPT;CTEMP (MAXPLT*MAXNPT)
REAL*4 SUSDHT,PNOM,HTRAT
REAL*4 SUPCST,MRCST
REAL*4 CTEMP,NEWCST
REAL*8 MILLI
INTEGER RD,WT,PUNCH,CARD,TAPE,ERRCOD,PHMIN,PHMAX
INTEGER*4 NEWCOD
INTEGER*2 IDNO,TYPENPTS,MWPT,NORDER,STATUS,MAINT,LOAD
LOGICAL*1 MINI,MIDI,MAXI,NPM,PCHING
C END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES
REAL*8 EPS/1.0D-3/
REAL*8 TRACE/1.0D-10/
INTEGER RD/5/,WT/6/,CARD/7/,TAPE/8/
INTEGER IDIMEN/500/
INTEGER MAXPLT/100/
INTEGER MAXPER/100/
INTEGER MAXNPT/5/
INTEGER NPERI/1/
REAL*8 ZERO/0.0D0/,ONE/1.0D0/,TWO/2.0D0/,HALF/0.5D0/,TEN/1.0D1/
$TENTH/1.0D-1/,HUNDRD/1.0D2/,CENTI/1.0D-2/,THOUS/1.0D3/,MILLI/1.0D-3/
END
SUBROUTINE SUPSIM
C SUPERVISOR OF ENTIRE SYSINT SIMULATION
**DEFINITION OF IMPORTANT VARIABLES**

- **AVLBTY** = Performance Probability (Percent)
- **CARD** = Unit Number for Computer Card Punch Device
- **CSTBTU** = Cost of Fuel (Cents/Megabtu)
- **CSTEMR** = Cost of Emergency Energy Purchases ($/MWh)
- **DAYS** = Duration of Period (Days)
- **DM** = Equivalent Load Curve Spacing (MW)
- **DT** = Duration of Period (Hours)
- **EMRP$** = Total Cost of Emergency Energy Purchases (Dollars)
- **ENERGY** = Energy Available as a Scarce Resource (GWh)
- **EPS** = Minimum Separation of IEMAX*DM and PEMAX (MW)
- **ERRCOD** = Accumulated Error Code
- **EXPBTU** = Expected Fuel Consumption (Megabtu)
- **EXPDEN** = Expected Energy Demand (GWh)
- **EXPEMR** = Expected Emergency Energy Purchases (GWh)
- **EXPGEN** = Expected System Generation (GWh)
- **EXPGWH** = Expected Plant Generation (GWh)
- **EXPHT** = Expected Hours of Operation
- **F** = Normalized Startup-Shutdown Frequency Function (Per Day)
- **GWHPER** = Energy Per Unit Area Under Load Curve (GWh) = DM*DT/1000
- **HTRAT** = Incremental Heat Rate (BTU/KWh)
- **IDIMEN** = Maximum Number of Points Allowed in Prob Array
- **IDNO** = Plant Identification Number
- **IDSTRG** = Strategy ID
- **IEMAX** = Prob Array Location of Maximum Load
- **IEMIN** = Prob Array Location of Minimum Load
- **INDEX** = Sequential Order of Plant as Read In
- **LDTYPE** = Type of Load Curve to be Used in This Period
- **LDTYPS** = Total Number of Load Curves Input
- **LOAD** = Normalized Load-Duration Curves (10**-4)
- **MAINT** = Numerically-Packed Maintenance Status
- **MAXI** = Option for Maximum Printout
- **MAXNPT** = Maximum Number of Valve Points Allowed
C MAXPER = MAXIMUM NUMBER OF PERIODS ALLOWED
C MAXPLT = MAXIMUM NUMBER OF PLANTS ALLOWED
C MIDI   = OPTION FOR MEDIUM VOLUME PRINTOUT
C MINI   = OPTION FOR MINIMUM PRINTOUT
C MRGCST = MARGINAL COST ($/MWH)
C MWPT   = VALVE POINT RATING (MW)
C NAME   = PLANT NAME
C NNORD  = NUMBER OF VALVE POINTS USED IN NORDER
C NOBASE = NUMBER OF ENTRIES IN NORDER IN BASE PORTION
C NOENTY = NUMBER OF ENTRIES TO NORDER
C NOPEAK = NUMBER OF ENTRIES IN NORDER TREATED AS PEAKERS
C NORDER = LOADING ORDER CODED AS 1000*NPT*INDEX
C NORDOP = STARTUP ORDER OPTION DESIRED
C NOSTNS = NUMBER OF STATIONS FOR WHICH DATA READ IN
C NPER   = NUMBER OF THIS PERIOD
C NPERS  = TOTAL NUMBER OF PERIODS READ IN
C NPER1  = ASSOCIATED VARIABLE FOR DIRECT ACCESS DEVICE; NPER1=NPER
C NPM    = NUCLEAR POWER MANAGEMENT OPTION
C = (.TRUE.=N.P.M. PROBLEM, .FALSE.=SIMULATION ONLY)
C NPTS   = NUMBER OF VALVE POINTS OR CAPACITY INCREMENTS
C PCHMAX = NORDER POINT WHEN PROB PUNCHED AT MAX.NUKES
C PCHMIN = NORDER POINT WHEN PROB PUNCHED AT MIN.NUKES
C PDTITL = PERIOD TITLE
C PEMAX  = MAXIMUM EQUIVALENT LOAD (MW)
C PEMIN  = MINIMUM EQUIVALENT LOAD (MW)
C PKMW   = FORECAST PEAK LOAD FOR THE PERIOD (MW)
C PNCM   = PLANT NOMINAL AVAILABILITY FRACTION
C PROB   = EQUIVALENT LOAD CDF
C PROD$  = TOTAL SYSTEM PRODUCTION FUEL COST (DOLLARS)
C PUNCH  = OUTPUT DEVICE TO BE USED FOR PUNCHED OUTPUT
C RD     = UNIT NUMBER OF COMPUTER INPUT READING DEVICE
C SGTITL = STRATEGY TITLE
C SPNRES = SPINNING RESERVE REQUIREMENT (MW)
C STATUS = MAINTENANCE STATUS
C = (0=NON-EXISTENT,1=DOWN,2=ON-LINE)
C SUPCST = STARTUP-SHUTDOWN COST (DOLLARS)
COMMON VARIABLES
COMMON/PLTDAT/IDNO(100), NAME(100), TYPE(100), SUSDHT(100), PNCM(100), $NPTS(100), MWPT(5, 100), HTRAT(5, 100)
COMMON/PERDAT/AVLBTY(100), CSTBTU(100), STATUS(100), EXPHRS(100), $EXPBTU(100), EXPGWH(100), NORDER(500), COST(100), ENERGY(100), $SUPCST(100), MRGCST(5, 100)

END OF DEFINITIONS
REAL*8 (A-H, O-$)
COMMON VARIABLES
VARIABLES DIMENSIONED IN MULTIPLES OF MAXPLT, MAX NO. OF STATIONS
COMMON/PLTDAT/IDNO(100), NAME(100), TYPE(100), SUSDHT(100), PNCM(100), $NPTS(100), MWPT(5, 100), HTRAT(5, 100)
COMMON/PERDAT/AVLBTY(100), CSTBTU(100), STATUS(100), EXPHRS(100), $EXPBTU(100), EXPGWH(100), NORDER(500), COST(100), ENERGY(100), $SUPCST(100), MRGCST(5, 100)

OTHER VARIABLES COMMON TO SEVERAL SUBRoutines
COMMON/PROB/DM, DT, GWHPER, DAYS, IEMIN, IEMAX, PEMIN, PEMAX, PROB(500)
COMMON/FLOAT/FPS, TRACE, PKMW, SPNRES, CSTEMR
COMMON/TITLE/SGTITL(10), PDTITL(10)
COMMON/INTEGR/RD, WT, PUNCH, CARD, TAPE, ERRCOD, NOSTNS, NPER, NPER, NPER1 $, IDSTRG, PCHIN, PCHMAX, MBRNUM
COMMON/LOGINFO/LDTYPE, LDTYPS, LOAD(50, 25), NORDOP, NOENTRY, NOBASE, $NOPEAK, NNORD
COMMON/MAXIMUM/IDIMEN, MAXPLT, MAXPER, MAXNPT
COMMON/CONSTS/ZERO, ONE, TWO, HALF, TEN, TENTH, HUNDRD, CENTI, THOUS, MILLI
COMMON/LOGICAL/MINI, MIDI, MAXI, NPM, Pching
COMMON/SUSDF/F(20)
COMMON/MAINT/MAINT(100, 20)

MAINT IS DIMENSIONED (MAXPLT, MAXPER/5) THE 5 IS 511/INTEGER*2
COMMON/MURGER/CTEMP(500), NEWCOD(5), NEWCST(5), MPTS, IFRST, ILAST
NEWCST & NEWCOD ARE DIMENSIONED MAXNPT; CTEMP (MAXPLT*MAXNPT)
REAL*4 SUSDHT, PNOM, HTRAT
REAL*4 SUPCST, MRGCST
REAL*4 CTEMP, NEWCST

PAGE 5
REAL*8 MILLI
INTEGER RD, WT, PUNCH, CARD, TAPE, ERRCOD, PCHMIN, PCHMAX
INTEGER*4 NEWCOD
INTEGER*2 IDNO, TYPE, NPTS, MWPT, NORDER, STATUS, MAINT, LOAD
LOGICAL*1 MINI, MIDI, MAXI, NPM, PCHING

C END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES

DATA $SUPSI/'SUPSIM'/
INTEGER KEYWRD(7)/'STAR', 'SAVE', 'OUTP', 'PERI', 'STRA', 'CCMP', 'STOP'
$/,$PRIN$/'PRIN'/,$CARD$/'CARD'/,$TAPE$/TAPE'/,$MINI$/'MINI'/,$
$MIDI$/'MIDI'/,$MAXI$/'MAXI'/,$BSOM$/'SOM'/
LOGICAL*1 DOPERD(100)

C DOPERD DIMENSIONED BY MAXPER
DEFINE FILE 9(100,1000,U,NPER)

C IN DEFINE FILE STATEMENT, 100 IS MAXPER & 1000 IS 10*MAXPLT
MINI=.TRUE.
ASSIGN 10 TO NEXT
ERRCOD=0

10 KEY=KEY+1
15 KEY=KEY+1
20 READ(RD,900) KEY1, I, KEY2, J, KEY3
WRITE(WT,910) $SUPSI,KEY1, I, KEY2, J, KEY3
40 IF(KEY1.EQ.KEYWRD(KEY)) GO TO (50,20,60,80,90,100,140), KEY
   KEY=KEY+1
   IF(KEY.GE.8) CALL ERRMSG('SUPSIM',6)
   GO TO 40

C START CONTROL CARD READ
50 ERRCOD=0
   CALL CMPTIM('SUPSIM','BASIC ')
   CALL BASIC
   CALL CMPTIM('BASIC ','SUPSIM')
   GO TO 20
60 IF(KEY2.EQ.$PRIN$) GO TO 70

C OUTPUT TAPE OR OUTPUT CARD CONTROL CARD READ
PUNCH=0
IF(KEY2.EQ.$TAPE$) PUNCH=TAPE

PAGE 6
IF(KEY2.EQ..$CARD$) PUNCH=CARD
PUNCH=PUNCH.GT.0
GO TO 30

C
OUTPUT PRINT  CONTROL CARD READ
70 MIDI=.FALSE.
MAXI=.FALSE.
IF(KEY3.EQ..$MAXI$.OR.KEY3.EQ..$MIDI$) MIDI=.TRUE.
IF(KEY3.EQ..$MAXI$) MAXI=.TRUE.
GO TO 30

C
PERIOD  CONTROL CARD READ
80 DO 85 I=1,NCSTNS
85 AVLBTY(I)=HUNDRED*PNOM(I)
CALL ERASE(CSTBTU,2*MAXPLT,ENERGY,2*MAXPLT,NORDER,MAXPLT+MAXNPT/2)
IF(MIDI) CALL CMPTIM('SUPSIM','PERIOD')
CALL PERIOD
IF(MIDI) CALL CMPTIM('PERIOD','SUPSIM')

C
STRATEGY CONTROL CARD READ
90 IF(MIDI) CALL CMPTIM('SUPSIM','STRATG')
CALL STRATG
IF(MIDI) CALL CMPTIM('STRATG','SUPSIM')
GO TO 20

C
COMPUTE  CONTROL CARD READ
100 IF(KEY2.NE..$BSOM$) GO TO 104
REAC(RD,915) (DOPERD(J),J=1,NPERS)
DO 102 N=1,NPERS
IF(DOPERD(N)) WRITE(WT,916) N
102 CONTINUE
GO TO 108

104 DO 106 N=1,NPERS
106 DOPERD(N)=.TRUE.
108 KEY2=ERRCOD
CALL CMPTIM('COMPUT')

C
WRITE BASIC PLANT INFO FOR THIS STRATEGY
WRITE(WT,920)
WRITE(WT,930) IDSTRG,SGTITL,NPM,MBRNUM
IF(NPM) WRITE(WT,935)
IF(PCHING) CALL PUNCHR(1)
WRITE(WT,940) NOSTNS
WRITE(WT,950) (IDNO(J),NAME(J),MWPT(NPTS(J),J),TYPE(J),SUSDHT(J),$PNCM(J),NPTS(J),(MWPT(I,J),HTRAT(I,J),I=1,MAXNPT),J=1,NOSTNS)
WRITE(WT,970) (1,1=1,9)
KEY1=(NPERS+4)/5
DO 110 I=1,NOSTNS
110 WRITE(WT,971) IIDNO(I),(MAINT(I,J),J=1,KEY1)
WRITE(WT,960) F
IF(PUNCH.LT.0) GO TO 130
ASSIGN 120 TO NEXT
DO 120 N=1,NPERS
IF(.NOT.DOPERD(N)) GO TO 120
NPER=N
NPER1=NPER
ERRCOD=KEY2
IF(MIDI) CALL CMPTIM('SUPSIM','PRESIM')
CALL PRESIM
IF(MIDI) CALL CMPTIM('PRESIM','SUPSIM')
IF(PCHING) CALL PUNCHR(5)
IF(.NOT.MINI) GO TO 135
120 CONTINUE
ASSIGN 10 TO NEXT
ERRCOD=KEY2
130 CALL CMPTIM('COMPUT','')
GO TO 15
ENTRY QUIT
135 IF(PCHING) CALL PUNCHR(6)
GO TO NEXT,(10,120)
C STOP CONTROL CARD READ
140 CALL ERRMSG('SUPSIM',8)
RETURN
900 FORMAT(2(A4,A3),3A4)
910 FORMAT(/T12,'KEY1 KEY2 KEY3'/'2X,A6,''=,'2(A4,A3),3A4)
915 FORMAT(80L1)
916 FORMAT(' SIMULATE PERIOD',I4)
920 FORMAT('I/'+30('O/'),4(' ',132('O/')+',132('*'))/
S $ /30('O/'),6(' ',132('O/')+',132('*'))/
930 FCRMAT('OSTRATEGY ID = ',16,5X,'TITLE :"",10A7,","",3X,
$'PUNCH NAME='*,L1,17)
935 FORMAT('O',T25,'** ** ** NUCLEAR POWER MANAG',
$'EMENT STUDY ** ** **)
940 FORMAT('O'," PLANT DATA FOR',I4,' STATIONS"/
$' INDEX IDNO NAME MAXMW TYPE SUSDHT(MEGABTU) PNOM NPTS',
$' MWPT(I,INDEX),HTRAT(I,INDEX),I=1,NPTS ',
$'MWPT IN MW & HTRAT IN BTU/KWH")
950 FORMAT((I4,18,A6,16,5X,A1,F14.2,F11.5,I3,5(2X,14,F7.0)))
960 FORMAT(' NORMALIZED STARTUP & SHUTDOWN',
$' FUNCTION :/(8F10.6))
970 FORMAT('I4,17,4X,2015)
971 FCRMAT(I4,I7,4X,2015)
END
REAL*4 SUSDHT, PNOM, HTRAT
REAL*8 MILLI
INTEGER RD, WT, PUNCH, CARD, TAPE, ERR, RCD, PCHMIN, PCHMAX
INTEGER*2 IDNO, TYPE, NPTS, MWPT, NORDER, STATUS, MAINT, LOAD
C END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES
DATA $BASIC/'BASIC'/,
       $PLAN/'PLAN'/,$NORM'/NORM'/,$LOAD'/LOAD'/,
       $SAVE'/SAVE'/,
$PLAN$/'PLAN'/,$NORM$/'NORM'/,$LOAD$/'LOAD'/,
       $SAVE$'SAVE'/,
$PLAN$/'PLAN'/,$NORM$/'NORM'/,$LOAD$/'LOAD'/,
       $SAVE$'SAVE'/,
10 REAC(RD,900) KEY1, (PROB(I), I=1,6)
WRITE(WT,910) $BASIC,KEY1, (PROB(I), I=1,6)
IF(KEY1.EQ.$PLAN$) GO TO 20
IF(KEY1.EQ.$NORM$) GO TO 50
IF(KEY1.EQ.$LOAD$) GO TO 60
IF(KEY1.EQ.$SAVE$) RETURN
CALL ERRMSG(* BASIC*,6)
C READ PLANT DATA
20 READ (RD,920) NOSTNS
WRITE(WT,930) NOSTNS
READ (RD,940) (IDNO(J), NAME(J), TYPE(J), SUSDHT(J), PNOM(J), NPTS(J),
       $(MWPT(I,J), HTRAT(I,J), I=1, MAXNPT), J=1, NOSTNS)
DO 40 J=1, NOSTNS
   I=NPTS(J)
30 IF(I.EQ.MAXNPT) GO TO 40
   I=I+1
   MWPT(I,J)=30000
   HTRAT(I,J)=1.E20
   GO TO 30
40 CONTINUE
WRITE(WT,950) (J, IDNO(J), NAME(J), MWPT(NPTS(J), J), TYPE(J), SUSDHT(J),
       $PNCM(J), NPTS(J), (MWPT(I,J), HTRAT(I,J), I=1, MAXNPT), J=1, NOSTNS)
   I=PRPNDX(J)
   GO TO 10
C READ-normalized startup & shutdown function
50 READ(RD,960) F
WRITE(WT,970) F
GO TO 10
READ LOAD TYPES
60 TEMP=TEN**4
READ(RD,920) LDTYPS
WRITE(WT,980) LDTYPS
IF(LDTYPS.GT.25) CALL ERRMSG('BASIC',6)
DO 90 I=1,LDTYPS
READ(RD,920) LDTYPE,NUMONE
WRITE(WT,921) LDTYPE,NUMONE
IF(NUMONE.LE.0) GO TO 75
DO 70 J=1,NUMONE
70 PROB(J)=ONE
75 KEY1=NUMONE+1
READ(RD,960) (PROB(J),J=KEY1,50)
WRITE(WT,990) (PROB(J),J=1,50)
IF(PROB(50).GT.ZERO) WRITE(WT,991)
C STORE LOAD TYPES IN UNITS OF 10**-4 (SAVES STORAGE)
DO 80 J=1,50
80 LOAD(J,LDTYPE)=PROB(J)*TEMP+HALF
90 CONTINUE
GO TO 10
900 FORMAT(2(A4,A3),3A4)
910 FORMAT(//T12,'KEY1 KEY2 KEY3/2X,A6,' : ',2(A4,A3),3A4)
920 FORMAT(1615)
921 FORMAT(/,215)
930 FORMAT('1','BASIC NOW READING PLANT DATA FOR','I4',' STATICNS//
  $ INDEX IDNO NAME MAXMW TYPE SUSDHT(MEGABTU) PNOM NPTS',
  $ ' MWPT(I,INDEX) HTRAT(I,INDEX) I=1,NPTS ',
  $'MWPT IN MW & HTRAT IN BTU/KWH//')
940 FORMAT((14,A4,1X,A1,F10.0,F9.5,I1.5(I4,F6.0)))
950 FORMAT((14,I8,A6,16.5X,A1,F14.2,F11.5,I3,5(2X,I4,F7.0)))
960 FORMAT(8F10.4)
970 FORMAT('1','BASIC NOW READING NORMALIZED STARTUP & SHUTDOWN',
  $ FUNCTION :/(8F10.6))
980 FORMAT(10F10.4)
$T110,'THIS NON-ZERO END POINT')
END
SUBROUTINE PERIOD
C SYSINT VERSION 10-29-71
C READS PERIOD DATA AND STORES IT ON DIRECT ACCESS DEVICE
C
IMPLICIT REAL*8 (A-H,O-$)
C
COMMON VARIABLES
C VARIABLES DIMENSIONED IN MULTIPLES OF MAXPLT, MAX NO. OF STATIONS
COMMON/PLDAT/IDNO(100),NAME(100),TYPE(100),SUSDTH(100),PNCM(100),
$NPTS(100),MWP(5,100),HTRAT(5,100)
COMMON/PERDAT/AVLBTY(100),CSTBTU(100),STATUS(100),EXPHT(100),
$EXPBU(100),EXPGWHI(100),NORDER(500),COST(100),ENERGY(100),
$SUPCST(100),MRGCST(5,100)
C OTHER VARIABLES COMMON TO SEVERAL SUBROUTINES
COMMON/PROB/DN,DTGWHPER,DAYS,IEMIN,IEMAX,PEN,PENMAX,PROB(500)
COMMON/FLT/EPS,TRACE,PKMW,SPNRES,CEMER
COMMON/TITLE/STGTITL(10),PDSCMR(10)
COMMON/INT/RD,WT,PUNCH,CARD,TAPE,ERRCOD,NOSTNS,NPER,NPERS,NPERI
$,IDSTRG,PCHMIN,PCHMAX,MBNUN
COMMON/LDGNO/LDTYPE,LDTPS,LOAD(50,25),NORDP,NOENTY,NOBASE,
$NOPEAK,NNORD
COMMON/CONSTS/ZERO,ONE,TWO,HALF,TEN,TENTH,HUNDRED,CENTI,THOUS,MILLI
REAL*4 SUSDTH,PNCM,HTRAT
REAL*4 SUPCST,MRGCST
REAL*8 MILLI
INTEGER RD,WT,PUNCH,CARD,TAPE,ERRCOD,PCHMIN,PCHMAX
INTEGER*2 IDNO,TYPE,NPTS,MWP,NORDER,STATUS,MAINT,LOAD
C END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES
REAL*8 BTUCST(3)
INTEGER*2 TEST(3)/*F','N','P*/
LOGICAL*1 CHGCST(3),CHGAVL
EQUIVALENCE (BTUCST,CSTFG),(BTUCST2,CSTNUK),(BTUCST3,CSTPKG)
DATA $STRAT,$PERIO,$SUSD,$ALTER/*STRAT,'PERIO','SUSD','ALTER*/
DATA STARS/1.050/
WRITE(WT,900)
NPERS=0

C PERIOD CONTROL CARD READ
10 READ(RD,910) PDTITL
READ(RD,920) NPER,LDTYPE,PKMW,SPNRES,DM,DT,CSTEMR,CSTFOS,CSTNUK,
$CSTPKG,AVLALL
NPERS=NPERS+1
IF(SPRES.LT.ZERO) SPNRES=ZERO
DO 12 K=1,3
CHGCST(K)=BTUCST(K).GT.ZERO
IF(.NOT.CHGCST(K)) BTUCST(K)=STARS
12 CONTINUE
CHGAVL=AVLALL.GT.ZERO.AND.AVLALL.LT.HUNDRD+ONE
IF(.NOT.CHGAVL) AVLALL=STARS
WRITE(WT,930) PDTITLNPERLDTYPE.PKMW,SPNRES,DM,DT,CSTEMR,CSTFOS,
$CSTNUK,CSTPKG,AVLALL
IF(.NOT.CHGAVL) GO TO 16
DO 14 I=1,NOSTNS
14 AVLBTY(I)=AVLALL
DO 20 K=1,3
IF(.NOT.CHGCST(K)) GO TO 20
DO 18 I=1,NOSTNS
IF(TYPE(I).EQ.TEST(K)) CSTBTU(I)=BTUCST(K)
18 CONTINUE
20 CONTINUE
30 READ(RD,940)$KEY1,$KEY2,ID,CST,AVL,ENER
IF($KEY1.EQ.$PERIO.OR.$KEY1.EQ.$PERIO) GO TO 50
IF($KEY1.EQ.$SUSDB) GO TO 40
IF($KEY1.EQ.$ALTER) GO TO 31
WRITE(WT,950) $KEY1,$KEY2,ID,CST,AVL,ENER
CALL ERRMSG('PERIOD',6)
C ALTER CARD WAS READ
31 INDEX=ININDEX(ID)
IF(CST.NE.ZERO) GO TO 32
CST=STARS
GO TO 33
32 CSTBTU(INDEX)=CST
33 IF(AVL.GT.ZERO) GO TO 34
   AVL=STARS
   GO TO 35
34 AVLBTY( INDEX)=AVL
35 IF(ENER.GT.ZERO) GO TO 36
   ENER=STARS
   GO TO 37
36 ENERGY(INDEX)=ENER
37 WRITE(WT,950) $KEY1,$KEY2,ID,CST,AVL,ENER
   GO TO 30
C SUSD DATA CONTROL CARD READ
40 WRITE(WT,951)$KEY1,$KEY2
   REAC(RD,970) NORDOP,NOENTY,NOBASE,NOPEAK
   WRITE(WT,960) NORDOP,NOENTY,NOBASE,NOPEAK
   REAC(RC,970) (NORDER(I),I=1,NOENTY)
   WRITE(WT,970) (NORDER(I),I=1,NOENTY)
   GO TO 30
50 WRITE(WT,980)(I,IDNO(I),NAME(I),CSTBTU(I),AVLBTY(I),ENERGY(I),
   $I=1,NOSTNS)
   WRITE(WT,951)$KEY1,$KEY2
   NPER1=NPER
   WRITE(WT,NPER1)PDITITL,NPER,LDTYPE,PKMW,SPNRES,DM,DT,CSTEMR,NORDOP,
   $NOENTY,NOBASE,NOPEAK,CSTBTU,AVLBTY,NORDER,ENERGY
   IF($KEY1.EQ.$PERIO) GO TO 10
C STRATEGY CONTROL CARD READ
RETURN
900 FORMAT('OPERIOD NOW READING PER PERIOD DATA & STORING ON DIRECT'
   $,' ACCESS DEVICE'/)
910 FORMAT(10A8)
920 FORMAT(2I4,9F8.0)
930 FORMAT('OPERIOD TITLE :"",10A8,""/T83,'(CENTS PER MEGABTU)'/
   $ NPER LDTYPE PKMW(MW) SPNRES(MW) DM(MW) DT(HRS)*,
   $T63,'CSTEMR($/MWH) CSTFOS CSTNUK CSTPKG AVGALL(/)
   $I6,18,F12.0,F11.0,F12.2,F9.2,F13.3,8X,3(F6.3,3X),F9.4/
   $'SPECIFIC CHANGES INPUT ON ALTER CARDS :
   $/T18,'IDNO CSTBTU AVLBTY ENERGY')
FORMAT(2A5, I10, 3F10.4)
950 FORMAT(' ', 2A5, I10, 3F10.4)
951 FORMAT(/T12,'$KEY1$KEY2'// PERIOD : ',2A5/)
960 FORMAT(//T12,'$KEYI$KEY2/I
951 PERIOD : ')
970 FORMAT(16I5)
980 FORMAT(/' FINAL KEY PERIOD INFO:'/ $INDEX IDNO NAME CSTBTU AVLBTY ENERGY'/$ (I4, I8, A6, 2X, 3F10.4))
END
FUNCTION ININDEX(ID)
C SYINT VERSION 1-01-73
C FINDS INDEX CORRESPONDING TO A PARTICULAR IDNO
C ****************************************************** *******
C IMPLICIT REAL*8 (A-H, O-$)
C COMMON VARIABLES
C VARIABLES DIMENSIONED IN MULTIPLES OF MAXPLT, MAX. NO. OF STATIONS
COMMON/PLTDAT/IDNO(100),NAME(100),TYPE(100),SUSDHT(100),PNOM(100),
NPTS(100),MWPT(5,100),HTRAT(5,100)
$COMMON/INTEGR/RDWTPUNCH,CARDTAPEERRCODNOSTNSNPERNPERSNPER1
$,IDSTRG,PCHLINPCHMAX,MBRNUM
REAL*4 SUSDHT,PNOM,HTRAT
INTEGER RD,WT,PUNCH,CARD,TAPE,ERRCOD,NOSTNS,NPER,PNPER1
$, ID2NDX(100)
C END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES
C DIMENSION 100 ALLOWS FOR ALL TWO-DIGIT NUMBERS
IF(ID.LT.0.OR.ID.GT.9999) GO TO 20
IDNO(NOSTNS+1)=ID
I=ID2NDX(ID/100+1)-1
10 I=I+1
IF(ID.EQ.IDNO(I)) GO TO 30
GO TO 10
20 I=NOSTNS+1
30 IF(I.GT.NOSTNS) GO TO 50
INNDX=I
RETURN
C PREPARES ID2NDX FOR FASTER SEARCH BY LATER CALLS TO INNDX
ENTRY PRPNDX(JDUMMY)
PRPNDX=JIDUMMY
CALL ERASE(ID2NDX,100/2)
DO 40 I=1,NOSTNS
KEYID=IDNO(I)*10+1
IF(ID2NDX(KEYID).EQ.0) ID2NDX(KEYID)=I
40 CONTINUE
RETURN
50 WRITE (WT,900) ID
CALL ERREMSG('INNDEX',7)
INNDX=I
RETURN
900 FORMAT(T10,'INVALID IDNO = ',I10)
END
SUBROUTINE STRATG
C SYSINT VERSION 10-15-71
C READS STRATEGY INPUT AND FORMS MAINTENANCE CODE
C **********************************************************************
C IMPLICIT REAL*8 (A-H,O-$) 
C COMMON VARIABLES 
C VARIABLES DIMENSIONED IN MULTIPLES OF MAXPLT, MAX. NO. OF STATIONS
COMMON/PLTDAT/IDNO(100),NAME(100),TYPE(100),SUSDHT(100),PNOM(100),
$NPTS(100),MWPT(5,100),HTRAT(5,100)
C OTHER VARIABLES COMMON TO SEVERAL SUBROUTINES
COMMON/TITLE,SSTTTL(10),DPTT1L(10)
COMMON/INTEGR/RD,WT,PUNCH,CARD,TAPE,ERRCOD,NOSTNS,NPER,NPERS,NPER1
$,IDSTRG,PCHMIN,PCHMAX,MBRUNUM
COMMON/MAXIMUM/IDIMEN,MAXPLT,MAXPER,MAXNPT
LOGICAL*1 MINI,MIDI,MAXI,NPM,PCHING
COMMON/MAINT/MAINT(100,20)

C MAINT IS DIMENSIONED (MAXPLT,MAXPER/5) THE 5 IS 511/INTEGER*2
REAL*4 SUSDHT,PNGM,HTRAT
INTEGER RD,WT,PUNCH,CARD,TAPE,ERRGOD,PCHMIN,PCHMAX
INTEGER*2 IDNO,TYPE,NPTS,MWPT,NORDER,STATUS,MAINT,LOAD
COMMON/LOGIC/L/MINI,MIDI,MAXI,NPM,PCHING
C END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES
INTEGER*2 M(100),NOTZRO(2),NDOWN(20)
C DIMENSION M(MAXPER)

INTEGER $MAIN$/'MAIN'/,$BLANK/I
READ(RD,910) NPM,PLACE,IDSTRG,SGTITL
WRITE(WT,920) IDSTRG,SGTITL
IF(PLACE.LT.0) PLACE=9
MBRNUM=1000000*PLACE+IDSTRG
IF(IDSTRG.LT.0) MBRNUM=9999999
KEY1=NOT
IF(NPM) KEY1=$BLANK
READ(WT,925) KEY1,NPM,MBRNUM
WRITE(WT,930) KEY1,NPM,MBRNUM
READ(RD,930) KEY1,KEY2,KEY3
WRITE(WT,940) KEY1,KEY2,KEY3
IF(KEY1.NE.$MAIN$) CALL ERRMSG('STRATG',6)
LMAX=(NPERS+4)/5
CALL ERASE(MAINT,MAMLT*MAINT/10)
DO 50 I=1,NSTNS
READ(RD,950) ID,NAM,NOTZRO,NDOWN
INDEX=INDEXX(ID)
IF(NAM.NE.NAME(INDEX).AND.NAM.NE.$BLANK) CALL ERRMSG('STRATG',7)
IF(NOTZRO(1).LE.0) NOTZRO(1)=1
IF(NOTZRO(2).LE.0.OR.NOTZRO(2).GT.NPERS) NOTZRO(2)=NPERS
WRITE(WT,960) INDEX,IDNO(INDEX),NAME(INDEX),NOTZRO,NDOWN
CALL ERASE(M,MAINT/2)
NOT1=NOTZRO(1)
NOT2=NOTZRO(2)
DO 10 L=NOT1,NOT2
 10 M(L)=2
DO 20 L=1,20
IF(NDOWN(L).LT.NOT1.OR.NDOWN(L).GT.NOT2) GO TO 30
20 M(NDOWN(L))=1
30 DO 40 N=1,NPERS,5
40 MAINT(INDEX,(N+4)/5)=
       $M(N+4)+10*(M(N+3)+10*(M(N+2)+10*(M(N+1)+10*M(N))))
50 CONTINUE
WRITE(WT,970)(I,J=1,LMAX)
DO 60 I=1,NOSTNS
60 WRITE(WT,971)
IIDNO(I),(MAINT(I,J),J=1,LMAX)
RETURN
910 FORMAT(L3,,II6,p10A7)
920 FORMAT('1 STRATEGIC NOW PROCESSING STRATEGY DATA FOR IDSTRG =',110/'
       $0 STRATEGY TITLE :'' ,1A7,''' '/'
925 FORMAT('0******,A6,'A NUCLEAR POWER MANAGEMENT STRATEGY ****' ,
       $' NAME='' ,1A7,''' FOR PUNCH OPTION *****'' '/'
930 FORMAT(3A4)
940 FORMAT('0 KEY1'' ',' ,3A4//'
       $# INDEX IDNO NAME STARTUP RETIRE DOWN FOR REFUELING &/OR'
       $',' MAINTENANCE'/T29,'AFTER')
950 FORMAT(I4,A4,2X,2I5,2013)
960 FORMAT(I4,18,A6,15,18,6X,2014)
970 FORMAT(/,'T20,' MAINTENANCE STRATEGY BY PERIOD AND INDEX',
       $' (0=NON-EXISTENT;1=DOWN;2=ON-LINE)'/T115,'1',T62,'PERIOD'/
       $15X,9110,9X,'0''/ INDEX IDNO',4X,10('1234567890')/
971 FORMAT(I4,17,4X,2015)
END
SUBROUTINE PRESIM
SYINT VERSION 1-01-73
C PERFORMS PRE-SIMULATION DATA MANIPULATION FOR EACH PERIOD
C ***********************************************************************
C IMPLICIT REAL*8 (A-H,O-$)
C COMMON VARIABLES
C VARIABLES DIMENSIONED IN MULTIPLES OF MAXPLT, MAX NO. OF STATIONS
COMMON/PLTDAT/IDNO(100),NAME(100),TYPE(100),SUSDHT(100),PNCM(100),
       $NPTS(100),MWPT(5,100),HTRAT(5,100)
COMMON/PERDAT/AVLBTY(100),CSTBTU(100),STATUS(100),EXPHRS(100),
OTHER VARIABLES COMMON TO SEVERAL SUBROUTINES
COMMON/PROB/DMDTGWHPERDAYSIEMINIEMAX,PEMINPEMAXPROB(500)
COMMON/FLOAT/EPS,TRACE,PKMW,SPNRES,CSTEMR
COMMON/TITLE/SGTITL(10),PDTITL(10)
COMMON/INTEGR/RD,WT,PUNCH,CARD,TAPE,ERRCOD,NOSTNS,NPER,NPERS,NPER1
$IDSTRG,PCHMIN,PCHMAX,MBRNUM
COMMON/LDGNFO/LDTYPE,LDTYPES,LOAD(50,25),NORDOP,NOENTY,NOBASE,
$NOPEAK,NNORD
COMMON/MAXMUM/IDIMEN,MAXPLT,MAXPER,MAXNPT
COMMON/CONSTS/ZERO,ONE,TWO,HALF,TEN,TENTH,HUNDRED,CENTI,THOUS,MILLI
COMMON/LOGICL/Mini,Midi,Mai,Npm,Pching
COMMON/MAINT/MAINT(100,20)
C MAINT IS DIMENSIONED (MAXPLT,MAXPER/5) THE 5 IS 511/INTEGER*2
REAL*4 SUSDHT,PNOM,HTRAT
REAL*4 SUPCST,MRGCST
REAL*8 MILLI
INTEGER RD,WT,PUNCH,CARD,TAPE,ERRCOD,PCHMIN,PCHMAX
INTEGER*2 IDNO,TYPE,NPIS,MWPT,NORDER,STATUS,MAINT,LOAD
LOGICAL*1 MINI,MIDI,MAXI,NPM,Pching
C END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES
LOGICAL*1 PRINT
EQUIVALENCE (PRINT,MIDI)
REAL*4 TEMP4
FIND(9*NPER1)
C TRANSLATE MAINTENANCE CODE INTO STATUS
J=(NPER+4)/5
I=NPER+5-J*5
IDUM=10**(5-I)
DO 110 K=1,NOSTNS
110 STATUS(K)=MOD(MAINT(K,J)/IDUM,10)
C RETRIEVE PERIOD INFO FROM DIRECT ACCESS DEVICE
READ (9*NPER1)PDTITL,NPER,LDTYPES,PKMW,SPNRES,DM,DT,CSTEMR,NORDOP,
$NOENTY,NOBASE,NOPEAK,CSTBTU,AVLBTY,NORDER,ENERGY
C RESCALE LOAD-DURATION CURVE & CONVERT FROM DL SPACING (2% PKMW)
C TO DESIRED DM
        CALL ERASE(PROB,2*IDIMEN)
        TEMP=1.0-4
        IEMIN=0
        DO 10 J=1,50
            PROB(J)=LOAD(J,LDTYPE)*TEMP
            IF(PROB(J).GT.ONE-TRACE) IEMIN=J
            IF(PROB(J).LE.ZERO) GO TO 20
        10 CONTINUE
        J=50
        20 IEMAX=J
        DL=PKMW*ONE/IEMAX
        PEMAX=IEMAX*DL+EPS
        PEMIN=IEMIN*DL
        GWHPER=DL*DT*MILLI
        DAYS=DT/24.DO
        DMTEMP=DM
        DM=DL
        IF(.NOT.PRINT) GO TO 30
        WRITE(WT,930) IDSTRG,SGBTITL
        WRITE(WT,940) NPER,PDTITL
        WRITE(WT,920) DM,IEMAX,PEMAX,(PROB(K),K=1,IEMAX)
        TEMP=GWHNRG(ZERO,PEMAX)
        WRITE(WT,901) TEMP
        30 CALL NUSCAL(DL,DMTEMP)

C ADJUST FINAL POINT SO LATER LINEAR INTERPOLATION GIVES PROPER
C AREA UNDER THE CURVE (I.E., EXPECTED VALUE)
C PROB(IEMAX)=PROB(IEMAX)*HALF*(ONE+PEMAX/DM-IEMAX)
C PROB(IEMAX+1)=ZERO
C IEMAX=IEMAX+1
C PEMAX=IEMAX*DM+EPS
        IF(.NOT.PRINT) GO TO 40
        WRITE(WT,920) DM,IEMAX,PEMAX,(PROB(K),K=1,IEMAX)
        TEMP=GWHNRG(ZERO,PEMAX)
        WRITE(WT,902) TEMP
        40 DO 50 I=1,NCSTNS
TEMP4 = CSTBTU(I) * CENTI
SUPCST(I) = SUSDHT(I) * TEMP4
DO 50 J = 1, MAXNPT
   MRGCST(J, I) = HTRAT(J, I) * .001 * TEMP4
WRITE FINAL PERIOD CONFIGURATION
WRITE(WT, 930) IDSTRGSGTITL
WRITE(WT, 940) NPERPDTITL
IF (NORDOP.EQ.1) SPNRES = -2.D9
WRITE(WT, 950) PKMW, SPNRES, DT, LDTYPE
WRITE(WT, 960) DM, IEMAX, PEMAX, (PROB(K), K = 1, IEMAX)
WRITE(WT, 970) CSTEMR
WRITE(WT, 980) (I, IDNO(I), NAME(I), MWPT(NPTS(I), I), TYPE(I), STATUS(I), $AVLBTY(I), CSTBTU(I), SUPCST(I), ENERGY(I), NPTS(I), (MWPT(J, I), $MRGCST(J, I), J = 1, MAXNPT), I, I = 1, NOSTNS)
IF (MIDI) CALL CMPTIM('PRESIM', 'LDGORD')
CALL LDGORD
IF (MIDI) CALL CMPTIM('LDGORD', 'PRESIM')
IF (PCHING) CALL PUNCHR(2)
CALL CMPTIM('PRESIM', 'SYSGEN')
CALL SYSGEN
CALL CMPTIM('SYSGEN', 'PRESIM')
RETURN
901 FORMAT (/10X, 'GWHNRG(0, PEMAX) AT POINT 1=', F15.8)
902 FORMAT (/10X, 'GWHNRG(0, PEMAX) AT POINT 2=', F15.8)
920 FORMAT ('O', /10X, 'DM = ', F10.4, 10X, 'IEMAX = ', I5, 10X, 'PEMAX = ', $F12.4, /10X, 'PROB(K), K = 1, IEMAX', /, (1X, 10F13.9))
930 FORMAT ('I', /OSTRATEGY ID = ', I9, 10X, 'TITLE = ', '10A7', '')
940 FORMAT ('OPERIOD NUMBER = ', I9, 10X, 'TITLE = ', '10A8', '')
950 FORMAT ('O', /10X, 'PKMW', 'T22', 'SPNRES(MW)', 'T39', 'DT(HRS)', 'T54', 'LDTYPE' / $F15.2, 7X, F7.2, F15.2, 13)
960 FORMAT ('OCOST OF EMERGENCY POWER =', 'F8.4, $/MWH')
END
SUBROUTINE NUSCAL(DMOLD, DMNEW)
C SYSINT VERSION 10-15-71
C CHANGES SPACING OF PROB FROM DMOLD TO DMNEW
C***********************************************
C IMPLICIT REAL*8 (A-H,O-$)
C COMMON VARIABLES
C OTHER VARIABLES COMMON TO SEVERAL SUBROUTINES
COMMON/PROB/DM, DT, GWHPER, DAYS, IEMIN, IEMAX, PDMIN, PDMAX, PROB(500)
COMMON/FLOAT/EPSTRACE, PKMWSPNRES, CSTMR
COMMON/INTEGR/RT, PUNCH, CARD, TAPE, ERRCOD, NOSTNS, NPER, NPER1, NPER
COMM/NUM/IDIMEN, MAXPLT, MAXPER, MAXNPT
COMMON/CONSTS/ZERO, ONE, TWO, HALF, TEN, TENTH, HUNDRD, CNTI, THOUS, MILLI
COMMON/LOGICAL/MINI, MIDM, MAXI, NPM, PCHING
REAL*8 MILLI
INTEGER RT, PUNCH, CARD, TAPE, ERRCOD, PDMIN, PDMAX
LOGICAL MINI, MIDI, MAXI, NPM, PCHING
C END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES
IF(DMOLD.EQ.DMNEW) RETURN
PDUM=PEMAX
IEMU=IEMAX+1
GOAL=GWHRG(ZERO, PDMAX)
GOAL = EXPECTED DEMAND UNDER PROB VS DMOLD
IF(.NOT. MIDI) GO TO 5
WRITE(WT, 1)
WRITE(WT, 910) GOAL
WRITE(WT, 920) DM, IEMAX, PDMAX,(PROB(I), I=1, IEMAX)
5 DM=DMNEW
GWHPER=DM*DT*MILLI
IEMAX=PEMAX/DM
IF(IEMAX+ICUM.GT.IDIMEN) CALL ERRMSG('NUSCAL', 1)
TEMP=IEMAX*DM+EPS
IF(TEMP.GT.PDMAX) PDMAX=TEMP
IEMIN=IEMIN*DMOLD/DMNEW+EPS
PEMIN=IEMIN*DM
DO 10 I=1, IEMIN
10 PROB(I+IDUM)=ONE
   JLOW=IEMIN+1
   TEMP=(IDUM-1)*DMOLD
   JHI=TEMP/DM+ONE
   IF(JHI.GT.IEMAX) GO TO 30
   TEMP=PROB(IDUM-1)/(PDUM-TEMP)
   DO 20 I=JHI,IEMAX
   20 PROB(I+IDUM)=TEMP*(PDUM-I*DM)
30 JHI=JHI-1
C FIRST APPROX: PROB(INEW)=LINEAR INTERPOLATION OF OLD PROB
C AT INEW*DMNEW
   TEMP=DMNEW/DMOLD
   DO 40 I=JLOW,JHI
      FB=I*TEMP
      ILO=FB
      FB=FB-ILO
      IHI=ILO+1
   40 PROB(I+IDUM)=PROB(ILO)+FB*(PROB(IHI)-PROCB(ILO))
   DO 50 I=1,IEMAX
50 PROB(I)=PROB(I+IDUM)
   I=IEMAX
   IF(PROB(I).GT.ZERO) GO TO 59
   I=I-1
   IF(PROB(I).GT.ZERO) GO TO 58
51 I=I-1
   IF(PROB(I).LE.ZERO) GO TO 51
   IEMAX=I+1
58 PMAX=IEMAX*DM+EPS
59 TEST=GWHNRG(ZERO,PEMAX)
C TEST = EXPECTED DEMAND UNDER FIRST APPROX
   TRUERR=GOAL-TEST
   RELERR=DABS(TRUERR)/GOAL
   IF(RELERR.LT.TRACE) GO TO 100
   IF(RELERR.GT.MILLI) CALL ERRMSG('NUSCAL',3)
   IF(.NOT.MAXI) GO TO 60
   WRITE(WT,910) GOAL,TEST,TRUERR,RELERR
WRITE(WT,920) DM, IEMAX, PMAX, (PROB(I), I=1, IEMAX)

C SECOND APPROX : ADJUST INTERIOR POINTS UP OR DOWN EQUAL AMOUNT DP

   60 ILO = IEMIN+2
   IHI = IEMAX-1
   DP = TRUERR / (GWHPER * (IHI - ILO + 1))
   IF (CABS(DP) .GT. MILLI) CALL ERRMSG( 'NUSCAL', 3)
   DO 70 I = ILO, IHI
   70 PROB(I) = PROB(I) + DP
   IF (.NOT. MAXI) GO TO 75
   TEST = GWHNRG(ZERO, PMAX)
   WRITE(WT,910) GOAL, TEST
   WRITE(WT,930) DP
   WRITE(WT,920) DM, IEMAX, PMAX, (PROB(I), I=1, IEMAX)

C THIRD APPROX : AVERAGE POINTS IN VIOLATION AND CHECK TO SEE THAT
C THEY ARE LESS THAN 1 AND GREATER THAN 0

   75 IF (PROB(ILO) .LE. PROB(ILO-1)) GO TO 90
   PROB(ILO) = HALF * (PROB(ILC) + PROB(ILO-1))
   PROB(ILO-1) = PROB(ILO)
   IF (PROB(ILO) .LT. ONE) GO TO 100

   80 CALL ERRMSG( 'NUSCAL', 4)
   WRITE(WT,920) DM, IEMAX, PMAX, (PROB(I), I=1, IEMAX)
   RETURN

   90 IF (PROB(IHI) .GT. PROB(IEMAX)) GO TO 100
   PROB(IHI) = HALF * (PROB(IHI) + PROB(IEMAX))
   PROB(IEMAX) = PROB(IHI)
   IF (PROB(IHI) .LE. ZERO) GO TO 80

C EXIT IF REASONABLE NEW PROB OBTAINED

   100 IF (.NOT. MIDI) RETURN
   TEST = GWHNRG(ZERO, PMAX)
   WRITE(WT,910) GOAL, TEST
   WRITE(WT,920) DM, IEMAX, PMAX, (PROB(I), I=1, IEMAX)
   RETURN

   1 FORMAT('NUCAL ENTERED TO CHANGE SPACING OF PROB')
   910 FORMAT(5(/), T7, 'GOAL', T22, 'TEST', T37, 'TRUERR', T52, 'RELERR', /,
     $3F15.6, E15.6)
SUBROUTINE LDGORD
C
C SETS UP NORDER FOR THE SPECIFIED OPTION NORDOP
C
C ***********************************************************************
C IMPLICIT REAL*8 (A-H,O-$)
C
C CCMMCN VARIABLES
C VARIABLES DIMENSIONED IN MULTIPLES OF MAXPLT, MAX. NO. OF STATIONS
COMMON/PLTCAT/IDNO(100),NAME(100),TYPE(100),SUSDHT(100),PNOM(100),
$NPTS(100),MWPT(5,100),HTRAT(5,100)
COMMON/PERDAT/AVLBTY(100),CSTBTU(100),STATUS(100),EXPFRS(100),
$EXPBTU(100),EXPGWH(100),NORDER(500),COST(100),ENERGY(100),
$SUPCST(100),MRGCST(5,100)
C OTHER VARIABLES COMMON TO SEVERAL SUBROUTINES
COMMON/INTEGR/RD,WTPUNCHCARDTAPEERRCODNOSTNSNPERNPERSNPERI,
$,IDSTRG.PCHMINPCHMAXMBRNUM
COMMON/LDGNFO/LDTYPELDTYPS.LOAD(50,25),NORDOPNOENTY,NOBASE,
$NOPEAK,NORD
COMMON/MAXMUM/IDIMEN,MAXPLT,MAXPER,MAXNPT
COMMON/CONSTS/ZERO,ONE,TWO,HALF,TEN,TENTH,HUNDRD,CENTI,THOUS,MILLI
COMMON/LOGICL/MINI,MIDI,MAXI,NPM,PCHING
COMMON/MURGER/CTEMP(500),NEWCOD(5),NEWCST(5),MPTS,IFIRST,ILAST
C NEWCST & NEWCOD ARE DIMENSIONED MAXNPT;CTEMP (MAXPLT*MAXNPT)
REAL*4 NORDER,PPP,PPP
REAL*4 SUPCST,MRGCST
REAL*4 CTMP,PEMAX
REAL*8 MILLI
INTEGER RDP,WT,PUNCH,CARD,TAPE,ERRCOD,PCHMIN,PCHMAX
INTEGER*4 NEWCOD
INTEGER*2 IDNO,TYPE,NPTS,MWPT,NORDER,STATUS,MAINT,LOAD
LOGICAL*1 MINI,MIDI,MAXI,NPM,PCHING
C
C END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES
DATA $ONLY/1.DO/
INTEGER*2 NTEMP(500), MWSPIN(500)
C NTEMP AND MWSPIN ARE DIMENSIONED MAXPLT*MAXNPT
NAMELIST/ERRDAT/NORDOP, NOENTY, NOBASE, NOPEAK, IFRST, ILAST, INDEX, NPT,
$MPTS, ID, I, SPIN, NORDER, NTEMP
CALL COMPRS(NTEMP)
WRITE(WT,940) NORDOP, NOENTY, NOBASE, NOPEAK, (NTEMP(I), I=1,NOENTY)
C ENCODE THOSE VALVE POINTS IN BASE PORTION
ISWTCH=NOENTY-NOPEAK+1
NOBASP=NOBASE+1
IFIRST=NOBASE
ILAST=NOBASE
CTEMP(ILAST+1)=1.E50
NORDER(ILAST+1)=1001
SPINXS=-SPNRES
DO 120 INDEX=1,NOSTNS
NPT=0
ID=IDNC(INDEX)
DO 70 NORD=1, NOBASE
IF(NTEMP(NORD).NE.ID) GO TO 70
NPT=NPT+1
NORDER(NORD)=1000*NPT+INDEX
CTEMP(NORD)=MRGCST(NPT, INDEX)
70 CONTINUE
IF(NPT.EQ.0) GO TO 120
MPTS=NPTS(INDEX)-NPT
IF(MPTS) 80, 105, 90
C ANY ONE OF SEVERAL ERRORS
80 WRITE(WT, ERRDAT)
CALL ERRMSG('LDGORD', 9)
90 SPINXS=SPINXS+
$CENTI*AVLBTY(INDEX)*(MWPT(NPTS(INDEX), INDEX)-MWPT(NPT, INDEX))
DO 100 I=1, MPTS
MPT=NPT+I
NEWCOD(I)=1000*MPT+INDEX
100 NEWCST(I)=MRGCST(MPT, INDEX)
ILAST=ILAST+MPTS
CTEMP(ILAST+1)=1.E50
NORDER(ILAST+1)=1001
CALL MERGER
105 IF(NOBASE.EQ.NOENTY) GO TO 120
    DO 110 I=NCBASP,NOENTY
    IF(NTEMP(I).EQ.ID) GO TO 80
110 CONTINUE
120 CONTINUE
    IF(NOBASE.EQ.NOENTY) GO TO 205
C STARTUP INTERMEDIATE PLANTS ACCORDING TO SPINNING RESERVE REQ.
C OR ECONOMICS
IPTR=NOBASP
NEXTID=NTEMP(IPTR)
NXNIDX=INDEX(NEXTID)
REASON=ZERC
K=0
140 IF(ILAST-IFRST+1) 80,141,142
141 K=1
142 NPT=NORDER(IFRST)/1000
    INDEX=NORDER(IFRST)-NPT*1000
    DSPIN=CENTI*AVLBTY(INDEX)*(MWPT(NPT,INDEX)-MWPT(NPT-1,INDEX))
    IF(DSPIN.GT.SPINXS+HALF) GO TO 150
C SPINNING RESERVE OK WITH PLANTS ALREADY STARTED
    IF(MRGCS(1,NXTNDX).LT.CTEMP(IFRST)) GO TO 150
C NEXT VALVE POINT LESS EXPENSIVE THAN NEXT PLANT
    SPINXS=SPINXS-DSPIN
    IFRST=IFRST+1
    GO TO 140
C START UP NEXT PLANT
150 IF(IPTR.NE.ISWTCH) GO TO 170
C FIRST PEAKING PLANT ABOUT TO BE STARTED
    IF(NOPEAK.EQ.0) GO TO 205
    IF(REASON.EQ.$ONLY) GO TO 170
    SPINXS=10.D6
    REASON=$ONLY
IF(NORDOP.EQ.4) GO TO 140
C NORDOP=4 PEAKERS COMMITTED ECONOMICALLY AFTER LAST INTERMEDIATE
C PLANT STARTED
C NORDOP<4 PEAKERS COMMITTED ECONOMICALLY AFTER ALL INTERMEDIATE
C EQUIPMENT
IFRST=ILAST+1
K=1
170 IF(IPTR.GT.NOENTY) GO TO 205
CTEMP(IFRST)=CTEMP(IFRST)-2.E-5
IF=INTEMP(IPTR)
NEXTID=INTEMP(IPTR+1)
NXTNDX=ININDEX(NEXTID)
IPTR=IPTR+1
INDEX=ININDEX(ID)
MPTS=NPTS(INDEX)
SPINXS=SPINXS+$CENTI*AVLBTY(INDEX)*(MWPT(MPTS,INDEX)-MWPT(1,INDEX))
I=2
IF(MPTS.EQ.1) GO TO 200
DO 180 I=2,MPTS
NEWCOD(I-K)=1000*I+INDEX
180 NEWCST(I-K)=MRGCST(I,INDEX)
IF(K.EQ.1) GO TO 202
DO 190 I=2,MPTS
NEWCOD(I-1)=NEWCOD(I)
NEWCST(I-1)=NEWCST(I)
IF(NEWCST(I).GE.CTEMP(IFRST)) GO TO 200
190 CONTINUE
I=MPTS+1
200 NEWCST(I-1)=CTEMP(IFRST)
NEWCOD(I-1)=NORDER(IFRST)
202 NORDER(IFRST)=1000+INDEX
CTEMP(IFRST)=MRGCST(I,INDEX)
IFRST=IFRST+1
ILAST=ILAST+MPTS
CTEMP(ILAST+1)=1.E50
NORDER(ILAST+1)=1001
MPTS=MPTS-K
CALL MERGER
IF(MPTS.GT.0) K=0
GO TO 140
205 NNORD=ILAST
CALL RETMRG
SPIN=ZERO
CALL ERASE(NTEMP,MAXPLT*MAXNPT/2)
DO 230 I=1,NNORD
IF(NORDER(I).LE.1000) GO TO 80
NPT=NORDER(I)/1000
INDEX=NCORDER(I)-NPT*1000
IF(NPT.NE.NTEMP(INDEX)) GO TO 80
NTEMP(INDEX)=NPT
IF(NPT.EQ.1) GO TO 220
SPIN=SPIN-$CENTI*AVLBTY(INDEX)*(MWPT(NPT,INDEX)-MWPT(NPT-1,INDEX))
GO TO 230
220 SPIN=SPIN+$CENTI*AVLBTY(INDEX)*(MWPT(NPTS(INDEX),INDEX)-MWPT(1,INDEX))
230 MWSPIN(I)=SPIN
JJ=(NNORD+4)/5
I=JJ*5-NNORD
IF(I.EQ.0) GO TO 250
DO 240 J=1,I
NORDJ=NNORD+J
NCORDER(NORDJ)=0
MWSPIN(NORDJ)=-10000
240 CTEMP(NORDJ)=-1.E30
250 JJ5=JJ*5
DO 255 J=1,JJ5
255 NTEMP(J)=J
WRITE(WT,920) NNORD
WRITE(WT,930)(J,NORDER(J),CTEMP(J),MWSPIN(J),(NTEMP(J+I*JJ),
$NORDER(J+I*JJ),CTEMP(J+I*JJ),MWSPIN(J+I*JJ),I=1,4),J=1,JJ)
IF(CABS(SPIN).GT.HALF) GO TO 80
RETURN
920 FORMAT(/'LOADING ORDER (NORDER) AS (1000*NPT + INDEX) : ',10X,I5
$,' VALID ENTRIES : /1X,5('I , J NORDER MRGCST MWSPN*')','/')
930 FORMAT(('TOP STARTUP ORDER :',10X,'WITH NOROP=',I2,6X,'NOENTY=',I4,
$6X,'NOBASE=',I3,6X,'NOPEAK=',I3/(2CI5))
END
SUBROUTINE COMPRS(NTEMP)
C SYSINT
C PERFORM STATUS : IDNO CHECK AND THEN COMPRESS AND TRANSFER NORDER INTO NTEMP;
C ALTER MARGINAL COST CURVES AND OPTIMIZE STARTUP ORDER
C *******************************************
IMPLICIT REAL*8 (A-H,O-$)
COMMON VARIABLES
VARIABLES DIMENSIONED IN MULTIPLES OF MAXPLT, MAX NO. OF STATIONS
COMMON/PLTDAT/IDNO(100),NAME(100),TYPE(100),SUSDHT(100),PNCM(100),
$NPTS(100),MWPT(5,100),HTRAT(5,100)
COMMON/PERDAT/AVLBTY(100),CSTBTU(100),STATUS(100),EXPHRS(100),
$EXPBTU(100),EXPGWH(100),NORDER(500),COST(100),ENERGY(100),
$SUPCST(100),MRGCST(5,100)
OTHER VARIABLES COMMON TO SEVERAL SUBROUTINES
COMMON/INTEGR/RD,WT,PUNCH,CARD,TAPE,ERRCOD,NOSTNS,NPER,NPERS,NPERI
$,IDSTRG,PCHMIN,PCHMAX,MBRNUM
COMMON/LDGNFO/LDTYPE,LDTYPES,LOAD(50,25),NORDOP,NOENTY,NOBASE,
$NOPEAK,NORD
COMMON/MAXIMUM/IDIMEN,MAXPLT,MAXPER,MAXNPT
COMMON/CONSTS/ONE,TWO,HALF,TEN,TENTH,HUNDRED,CENTI,THOUS,MILLI
COMMON/LOGICL/MINI,MIDI,MAXI,NPM,PCHING
REAL*4 SUSDHT,PNOM,HTRAT
REAL*4 SUPCST,MRCGCT
REAL*8 MILLI
INTEGER RD,WT,PUNCH,CARD,TAPE,ERRCOD,PCHMIN,PCHMAX
INTEGER*2 IDNO,TYPE,NPTS,MWPT,NORDER,STATUS,MAINT,LOAD
LOGICAL*1 MINI,MIDI,MAXI,NPM,PCHING
C END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES
REAL*4 TEMP4
INTEGER*2 NTEMP(1),IPJ(3)

C CHECK CONSISTENCY OF NOBASE, NOPEAK & NOENTY
5 IF(NORDOP.EQ.1.OR.NOBASE.GT.NOENTY) NOBASE=NOENTY
   IF(NOBASE.LE.0) NOBASE=1
   NOPEAK=MINO(NOPEAK, NOENTY-NOBASE)
   NTEMP(NOENTY+1)=IDNO(1)
   IF(NORDER(1).EQ.0) GO TO 80
   CALL ERASE(NTEMP, MAXPLT*MAXNPT/2)

C FLAG OFF-LINE PLANTS & CHECK THAT EACH ON-LINE PLANT MENTIONED
DO 8 I=1, NOSTNS
   ID=IDNO(I)
   IS=STATUS(I)
   IF(IS.NE.2) IS=1
   DO 7 J=1, NOENTY
      IF(ID.EQ.NORDER(J)) GO TO (6,8), IS
   GO TO 7
6 NORDER(J)=0
7 CONTINUE
   IF(IS.EQ.2) WRITE(WT,911)ID
   IF(IS.EQ.2) CALL ERRMSG('COMPRS',9)
8 CONTINUE

C CONTROL SEGMENT OF NORDER COMPRESSED INTO NTEMP
IP=0
J=1
10 GO TO (20,30,40,45), J
20 IL0=1
   IHI=NOBASE
   GO TO 50
30 IL0=IHI+1
   IHI=NOENTY-NOPEAK
   IF(IHI.LT.IL0) GO TO 70
   GO TO 50
40 IL0=IHI+1
   IHI=NOENTY
   GO TO 50
45 NOBASE=IPJ(1)
  NOPEAK=IPJ(3)-IPJ(2)
  NOENTY=IPJ(3)
  NORDER(1)=0
  GO TO 5
C PERFORM COMPRESSION AND TRANSFER OF A SEGMENT
50 IF(ILO.GT.NCENTY) GO TO 70
  DO 60 I=ILO,IHI
  IF(NORDER(I).EQ.0) GO TO 60
  IP=IP+1
  NTEMP(IP)=NORDER(I)
  60 CONTINUE
70 IPJ(J)=IP
  J=J+1
  GO TO 10
C ALTER MARGINAL COST CURVES
80 IF(MIDI) WRITE(WT,901)
  DO 61 I=1,NCSTNS
  JJ=NPTS(I)
  J=J+1
  GO TO 61
C PUT MINIMUM AVERAGE COST IN MRGCST(1,I)
  TEMP4=MRGCST(1,I)*MWPT(I,I)
  IF (JJ.EQ.1) GO TO 61
  DO 1 J=2,JJ
  TEMP4=TEMP4+MRGCST(J,I)*(MWPT(J,I)-MWPT(J-1,I))
  1 MRGCST(1,I)=AMIN1(MRGCST(1,I),TEMP4/MWPT(J,I))
  SUM=ZERO
C LEVELIZE DECREASING MARGINAL COST CURVES
11 IF(JJ.LT.3) GO TO 55
  DO 51 J=3,JJ
  IF(MRGCST(J,I).GE.MRGCST(J-1,I)) GO TO 51
  SUM=ZERO
  DO 31 K=2,J
  SUM=SUM+MRGCST(K,I)*('NWPT(K,I)-MWPT(K-1,I))/(MWPT(J,I)-MWPT(1,I))
  31 DO 41 K=2,J
  41 MRGCST(K,I)=SUM
  GO TO 11
51 CONTINUE
55 IF(MINI) GO TO 61
   WRITE(WT,910) I,INDO(I),NAME(I),(MWPT(K,I),MRGCST(K,I),K=1,JJ)
   IF(SUM.NE.ZERO) WRITE(WT,920)
61 CONTINUE
   IF(NORDOP.LT.3) GO TO 170
   C OPTIMIZE STARTUP ORDER
   NO=NOENTY-(NOBASE+NOPEAK)
   IDUM=NOBASE
   IPJ(3)=2
   IF(NO.NE.0) GO TO 100
90 NC=NOPEAK
   IDUM=NOENTY-NOPEAK
   IPJ(3)=3
   IF(NO.EQ.0) GO TO 150
100 DO 110 J=1,NO
      ID=NTEMP(IDUM+J)
      NORDER(J)=INNDEX(ID)
110 NORDER(NO+J)=ID
   C START UP UNITS IN ORDER OF INCREASING MINIMUM AVERAGE COST
   IF(NO.EQ.1) GO TO 150
   DO 140 J=2,NO
      IPJ(1)=NORDER(J)
      IPJ(2)=NORDER(NO+J)
      IP=J
120 IP=IP-1
      IF(IP.EQ.0) GO TO 130
      IF(MRGST(1,IPJ(1)) .GE. MRGCST(1,NORDER(IP))) GO TO 130
      NORDER(IP+1)=NORDER(IP)
      NORDER(NO+IP+1)=NORDER(NO+IP)
      GO TO 120
   130 NORDER(IP+1)=IPJ(1)
      NORDER(NO+IP+1)=IPJ(2)
   140 CONTINUE
   150 DO 160 J=1,NO
   160 NTEMP(IDUM+J)=NORDER(NO+J)
IF(IPJ(3).NE.3) GO TO 90
170 CALL ERASE(NORDER,MAXPLT*MAXNPT/2)
    RETURN
C RETURN MARGINAL COST CURVES TO ORIGINAL VALUES
ENTRY RETMRG
DO 210 I=1,NOSTNS
    TEMP4=CSTBTU(I)*1.E-5
DO 210 J=1,MAXNPT
210 MRGCST(J,I)=HTRAT(J,I)*TEMP4
    RETURN
901 FORMAT('Il CCMPRS WILL TEMPORARILY LEVELIZE DECREASING MARGINAL',
    $' COST CURVES TO ALLOW PROPER INCREMENTAL LOADING.'$ IN ADDITION,
    $' MINIMUM AVERAGE COST WILL BE PLACED IN MRGCST(1,I).  'THUS,'$//
    $T5,'I',T8,'IDNO',T14,'NAME',T21,' (MWPT,MNAVGCST)',T50,'INCREASING
    $ MARGINAL COST CURVE')
910 FORMAT (I5,I6,A6,5('(' ,I4,' ',',F9.5,''))) $T5,I',T8,'IDNO',T14,'NAME',T21,' (MWPT,MNAVGCST)',T50,'INCREASING
911 FORMAT(///, 'UNLISTED IDNO OF CN-LINE PLANT=',I5)
920 FORMAT('+',T122,'LEVELIZED')
END
SUBROUTINE MERGER
C SYSINT VERSION 10-31-71
C MERGES NEWLY STARTED PLANT WITH PREVIOUSLY STARTED ONES
C ************************************************************
C IMPLICIT REAL*8 (A-H,O-$)
C COMMON VARIABLES
C VARIABLES DIMENSIONED IN MULTIPLES OF MAXPLT, MAX.NO. OF STATIONS
COMMON/PERCAT/AVLBTY(100),CSTBTU(100),STATUS(100),EXPHRS(100),
    $EXBTU(100),EXPWHT(100),NORDER(500),COST(100),ENERGY(100),
    $SUPCST(100),MRGCST(500),5)
C OTHER VARIABLES COMMON TO SEVERAL SUBROUTINES
COMMON/MAXIMUM/IDIMN,MAXPLT,MAXPER,MAXNPT
COMMON/MURGER/CTEMP(500),NEWCOD(5),NEWCST(5),MPTS,IFRST,ILAST
C NEWCST & NEWCOD ARE DIMENSIONED MAXNPT:CTEMP (MAXPLT*MAXNPT)
REAL*4 SUPCST,MRGCST
REAL*4 CTEMP,NEWCST
INTEGER*4 NEWCST
SUBROUTINE SYSGEN

C SYSINT VERSION 1-01-73

C SIMULATES SYSTEM GENERATION FOR ONE TIME PERIOD

C *******************************************************

IMPLICIT REAL*8 (A-H,O-$)

C COMMON VARIABLES

C VARIABLES DIMENSIONED IN MULTIPLES OF MAXPLT, MAX. NO. OF STATIONS

COMMON/PLTDAT/IDNO(100),NAME(100),TYPE(100),SUSDHT(100),FNCM(100),
$NPTS(100),MWPT(5,100),HTRAT(5,100)

COMMON/PERDAT/AVLBTY(100),CSTBTU(100),STATUS(100),EXPHRS(100),
$\text{EXPBTU(100), EXPGWH(100), NORDER(500), COST(100), ENERGY(100),}$

$\text{SUPCST(100), MRGCST(5, 100)}$

\begin{verbatim}
C OTHER VARIABLES COMMON TO SEVERAL SUBROUTINES
COMMON/PROB/DM, DT, GWHPER, DAYS, EMIN, EMAX, PMIN, PMAX, PROB(500)
COMMON/FLOAT/EPS, TRACE, PKM, SPNRES, CSTEMR
COMMON/TITLE/SGTITL(10), PDTITL(10)
COMMON/INTEGER/IT, PUNCH, CARD, TAPE, ERRCOD, NOSTNS, NPER, NPERS, NPER1
, IDSTRG, PCHMIN, PCHMAX, MBRNUM
COMMON/LDGNO/LDTYPE, LDTYPEP, LOAD(50, 25), NORDOP, NOENTY, NOBASE,
$\text{NOPEAK, NNORD}$
COMMON/MAXMUM/IDIMEN, MAXPLT, MAXPER, MAXNPT
COMMON/CONSTS/ZERO, ONE, TWO, HALF, TEN, TENTH, HUNDRED, CENTI, THOUS, MILLI
COMMON/LOGICL/MINI, MIDI, MAXI, NPM, PCHING
REAL*4 SUSDHT, PNM, HTRAT
REAL*4 SUPCST, MRGCST
REAL*8 MILLI
INTEGER RD, WT, PUNCH, CARD, TAPE, ERRCOD, PCHMIN, PCHMAX
INTEGER*2 IDNO, TYPE, NPTS, MWPT, NORDER, STATUS, MAINT, LOAD
LOGICAL*1 MINI, MIDI, MAXI, NPM, PCHING
\end{verbatim}

C END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES

\begin{verbatim}
C IDUM'S USED TO MAKE NAMELIST OUTPUT MORE READABLE
NAMELIST /FNLTOT/MWINST, MWONLN, MWPEAK, MWMRGN, MWSPIN, PLOFL,
$\text{EXPDEM, EXPGEN, XNKEN, IDUM1, XNKEN1, EXPMR, IDUM2, UNSRVD, PROD}$,
$\text{IDUM3, SNNRPD, SNNPRD, IDUM4, SUSD, SNKSPS, IDUM5, SNNSUP, SBTOT,}$
$\text{IDUM6, SNKTOT, SNTTOT, IDUM7, EMRPS, TOTAL}$
INTEGER*2 IDUM1, IDUM2, IDUM3, IDUM4, IDUM5, IDUM6, IDUM7
DATA IDUM1, IDUM2, IDUM3, IDUM4, IDUM5, IDUM6, IDUM7/7*0/
INTEGER*2 NUCL/"N"/
REAL*4 PLOFL
\end{verbatim}

C IDSTRG.LT.0 IS OPTIONAL RETURN TO CHECK INPUT
IF(IDSTRG.LT.0) RETURN
IF(MIDI) WRITE(WT,930)
CALL ERASE(EXPBTU, 2*MAXPLT, EXPGWH, 2*MAXPLT, EXPHRS, 2*MAXPLT)
EXPDEM=GWHNRM(ZERO, PMAX)
PE=ZERO
EXPOUT=ZERO
DOUBLE CHECK TO AVOID INADVERTENT PUNCHING

IF(NPM.AND.PCHING) GO TO 40
PCHMIN=-1
PCHMAX=-1

DO LOOP TO BUILD UP EQUIVALENT LOAD CDF

40 00 50 J=1,NNORD
L1=NORDER(J)
NPT=L1/1000
L=L1-NPT*1000
IF(STATUS(L).LE.1) GO TO 50
P=AVLBTY(L)*1.D-2
MWIN=0
IF(NPT.GT.1)MWIN=MWPT(NPT-1,L)
MWTOT=MWPT(NPT,L)
HTRATE=HTRAT(NPT,L)
MWADD=MWTOT-MWIN
EXPCUT=EXPRT+(ONE-P)*MWADD

SUBTRACT PLANT OF INTEREST
CALL SUBPLT(MWIN,P)
IF(MAXI) WRITE(WT,921) DM,IEMAX,PEMAX,(PROBIK),K=1, IEMAX)
TEMP= PE+MWADD

EVALUATES INCREMENT OF EXPECTED PRODUCTION
ENERGE=P*GWHNRG(PE,TEMP)
PE=TEMP

ADD THE PLANT OF INTEREST BACK IN
CALL ADDPLT(MWTOT,P)

EVALUATE & ACCUMULATE IMPORTANT PRODUCTION INFO
IF(NPT.EQ.1) EXPRS(L)=ENERGE*THOUS/MWPT(1,L)
EXPBU(L)=EXPBUTU(L)+ENERGE*HTRATE
EXPBWH(L)=EXPBWH(L)+ENERGE
IF(J.EQ.PCHMIN.OR.J.EQ.PCHMAX) CALL PUNCHR(IDINT(PE))
IF(.NOT.MIDI) GO TO 50
AVPROB=1.020
IF(MWADD.GT.0) AVPROB=ENERGE*THOUS/(P*DT*MWADD)
IF(MAXI) WRITE(WT,931)
WRITE(WT,940)LIDNO(L),PEMWIN,MWADDMWTOT.AVPROB.ENERGE,
$\text{EXPGWH(L),L}

\text{IF(MAXI) WRITE(WT,922) DM,IEMAX,PEMAX,(PROB(K),K=1,IEMAX)}

50 CONTINUE

\text{TEMP=GWHNRG(ZERO,PEMAX)}

\text{TEMP=TEMP-EXPDEN}

\text{APXOUT=TEMP*THOUS/DT}

\text{TEMP=(EXPOUT-APXOUT)*HUNDRED/(EXPOUT+1.D-20)}

\text{IF(DABS(TEMP)>CENTI) CALL ERRMSG(SYSGEN,5)}

\text{IF(.NOT.MIDI) GO TO 60}

\text{WRITE(WT,910) EXPOUT,APXOUT,TEMP}

\text{WRITE(WT,920) DM,IEMAX,PEMAX,(PROB(K),K=1,IEMAX)}

60 \text{UNSRVD=GWHNRG(PE,PEMAX)}

\text{PLOFL=PROBX(PE)}

\text{MWONLN=PE+EPS}

\text{MWPEAK=PKMW}

\text{MWMRGN=MWONLN-MWPEAK}

\text{MWSPIN=SPNRES}

\text{MWINST=0}

\text{PRODZ=ZERO}

\text{EXPGZ=ZERO}

\text{SUSDZ=ZERO}

\text{XNNGEN=ZERO}

\text{$\text{NNPRD}=\text{ZERO}$}

\text{$\text{NNNSUS}=\text{ZERO}$}

\text{TEMP=HUNDRED/DT}

\text{WRITE (WT,950) IDSTRG,SGTITL,NPER,PDTITL}

\text{DO 70 J=1,NOSTNS}

\text{IF(STATUS(J).GE.1) MWINST=MW INST+MWPT(NPTS(J),J)}

\text{FACT=EXPGWH(J)*THOUS/(MWPT(NPTS(J),J)*DT)}

\text{SUSD=SUSDNO(EXPHRS(J)*TEMP/AVLBTY(J))}

\text{SUSTU=SUSD*STBTD(J)}

\text{$\text{SUSD}=\text{SUSTU}*CSTBTD(J)*1.D-2$}

\text{SUSDZ=SUSDZ+$\text{SUSD}$}

\text{PRDBTU=EXPBTU(J)}

\text{EXPBTU(J)=EXPBTU(J)+SUSTU}

C EVALUATE AND PRINT FINAL PER PLANT RESULTS

\text{DO 70 J=1,NOSTNS}

\text{IF(STATUS(J).GE.1) MWINST=MW INST+MWPT(NPTS(J),J)}

\text{FACT=EXPGWH(J)*THOUS/(MWPT(NPTS(J),J)*DT)}

\text{SUSD=SUSDNO(EXPHRS(J)*TEMP/AVLBTY(J))}

\text{SUSTU=SUSD*STBTD(J)}

\text{$\text{SUSD}=\text{SUSTU}*CSTBTD(J)*1.D-2$}

\text{SUSDZ=SUSDZ+$\text{SUSD}$}

\text{PRDBTU=EXPBTU(J)}

\text{EXPBTU(J)=EXPBTU(J)+SUSTU}
$\text{SPROD} = \text{PRDBTU} \times \text{CSTBTU(J)} \times 1 \times 10^{-2}$

$\text{COST(J)} = \text{SPROD} + \text{SUSD}$

$\text{PRODS} = \text{PRODS} + \text{SPROD}$

$\text{EXPRGEN} = \text{EXPRGEN} + \text{EXPWH(J)}$

\[ \text{IF(TYPE(J).EQ.NUCL) GO TO 65} \]

$\text{XNNGEN} = \text{XNNGEN} + \text{EXPWH(J)}$

$\text{SNPRD} = \text{SNPRD} + \text{SPROD}$

$\text{SNSUS} = \text{SNSUS} + \text{SUSD}$

\[ \text{65 WRITE(WT,960) J,IDNO(J),NAME(J),FACT,EXPRHRS(J),SUSD,SUBTU,$SUSD,} \]

$\text{EXPRWH(J),PRDBTU,SPROD,EXPBTU(J),CCST(J),J}$

70 CONTINUE

C EVALUATE AND PRINT FINAL SYSTEM RESULTS

$\text{XNKGEN} = \text{EXPRGEN} - \text{XNNGEN}$

$\text{SNKPRD} = \text{PRODS} - \text{SNPRD}$

$\text{SNKSUS} = \text{SUSD} - \text{SNSUS}$

$\text{SNKTOT} = \text{SNKPRD} + \text{SNKSUS}$

$\text{SNNTOT} = \text{SNPRD} + \text{SNSUS}$

$\text{SSBTOT} = \text{SNKPRD} + \text{SNKSUS}$

$\text{EMPRS} = \text{EXPREM*THOUS*CSTEMR}$

$\text{TOTALS} = \text{PRODS} + \text{SUSD} + \text{EMPRS}$

\[ \text{WRITE(WT,970) MWINST,MWCLNLN,MWPEAK,MWMRGN,MWSPIN,PLOFL} \]

\[ \text{WRITE(WT,980) EXPRDEM,EXPRGEN,XNNGEN,EXPRMR,UNSRVD} \]

\[ \text{WRITE(WT,990) PRODS,SNKPRD,SNPRD,SUSD,SNSUS,SNKSUS,} \]

$\text{SSBTOT,SNKTOT,SNNTOT,CSTEMR,EMPRS,TOTALS}$

\[ \text{IF(PCHING) WRITE(PUNCH,FNLTOT)} \]

RETURN

910 FORMAT('(/T10,''TRUE EXP. OUTAGE ='''',F8.2,''' MW'/''$T10,''APPROX. EXP. OUTAGE ='''',F8.2,''' MW'/''$T10,''ERROR IN APPROX. =''',F9.5,''' %'//''$1 FINAL EQUIVALENT LOAD CDF:')

920 FORMAT('/10X,*DM = '''',F10.4,10X,*IEMAX = '''',I5,10X,*PEMAX = '''',

$F12.4,''/10X,*PROB(K),K=1,*,IEMAX *,/,(1X,10F13.9))$

921 FORMAT('0',132('*')/

$ *WITHOUT PLANT OF INTEREST  PROB(K),K=1,*,IEMAX : 

$ DM = '''',F8.2,5X,*IEMAX = '''',I5,5X,*PEMAX = '''',F12.4/(10F13.9))
SUBROUTINE SUBPLT(MW,P)
C SYSINT VERSION 1-01-73
C SUBTRACTS PLANT OF MW MEGAWATTS AND P FRACTIONAL AVAILABILITY
C FROM FRCM PROB, THE EQUIVALENT LOAD CDF
C NOTE: MW MUST BE LESS THAN OR EQUAL TO PEMIN
C *******************************************************
C IMPLICIT REAL*8 (A-H,O-$)
C COMMON VARIABLES
C OTHER VARIABLES COMMON TO SEVERAL SUBROUTINES
COMMON/PROB/DM,DT,GWHPER,DAYS,IEMIN,IEMAX,PEMIN,PEMAX,PROB(500)
COMMON/FLOAT/EPSTRACEPKMWSPNRES,CSTEMR,
COMMON/CONSTS/ZEROCNETWOHALFTEN,TENTHHUNDRDCENTITHOUS,MILLI
REAL*8 MILLI
C END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES
IF(MW.LE.0) RETURN
IF(MW.LE.PEMIN) GO TO 10
CALL ERRMSG('SUBPLT',2)
RETURN
10 ILOW=IEMIN+1
FB=MW/DM
INT=FB
FB=FB-INT
QV=ONE/P
Q=ONE-P
QFB=Q*FB
GAMMA=ONE/(ONE-QFB)
IF(INT.GT.0) GO TO 60
C LOOP TO UNCCNVOLVE PLANT IF MW.LT.DM
DO 20 J=ILOW,IEMAX
20 PROB(J)=GAMMA*(PROB(J)-QFB*PROB(J-1))
C FIND NEW PEMAX AND IEMAX
30 J=IEMAX
40 IF(PROB(J).GT.TRACE) GO TO 50
PROB(J)=ZERO
J=J-1
GO TO 40
50 IF(IEMAX.EQ.J) RETURN
   IEMAX=J+1
   PEmax=IEMAX*DM+EPS
   RETURN
C LOOP TO UNCONVOLVE PLANT IF MW.GE.DM
60 DO 70 J=ILCW,IEMAX
   JNT=J-J-INT
   PROB(J)=OVP*(PROB(J)-Q*(PROB(JINT)+FB*(PROB(JINT-1)-PROB(JINT))))
GO TO 30
END
FUNCTION GWHNRG(XLOWER,XUPPER)
C SYSINT
VERSION 10-15-71
C CALCULATES GWH OF ENERGY UNDER PORTION OF PROB, THE CDF OF
C EQUIVALENT LOAD, BY INTEGRATING FROM XLOWER TO XUPPER ASSUMING
C LINEAR INTERPOLATION BETWEEN ARRAY POINTS
C ***********************************************
IMPLICIT REAL*8 (A-H,O-S)
C COMMON VARIABLES
C OTHER VARIABLES COMMON TO SEVERAL SUBROUTINES
COMMON/PROB/DM,DT,GWHER,DAYS,IEMIN,IEMAX,PEMIN,PEMAX,PROB(500)
COMMON/CONSTS/ZERO,ONETWOHALFTEN,TENTHUNDRED,CENTI,THOUS,MILLI
REAL*8 MILLI
C END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES
C XLO=XLOWER
XUP=XUPPER
GWHNRG=ZERO
SUM=ZERO
IF( XLO.GE.XUP) RETURN
IBELO=XLO/DM
ILAST=XUP/DM
IF( IBELO.LE.0 .OR. ILAST.GE.IEMAX) GO TO 50
C STANDARD CASE WITH BOTH POINTS WITHIN NON-ZERO ARRAY POINTS
5 IFRST=IBELO+1
IABOV=ILAST+1
IFRSTP=IFRST+1
ILASTM=ILAST-1
ICASE=IABOV-IBELO
RLC=IFRST-XLO/DM
RUP=XUP/DM-ILAST
PLO=PROB(IFRST)+(PROB(IBELO)-PROB(IFRST))*RLO
PUP=PROB(IABOV)+(PROB(ILAST)-PROB(IABOV))*(ONE-RUP)
GO TO (10,20,30,40),ICASE
40 DO 35 I=IFRSTP,ILASTM
35 SUM=SUM+PROB(I)
30 SUM=SUM+HALF*(PROB(IFRST)+PROB(ILAST))
20 SUM=SUM+HALF*(RLO*(PLO+PROB(IFRST))+RUP*(PUP+PROB(ILAST))
15 GWHNRG=SUM*GWHPER
RETURN
10 SUM=SUM+(XUP-XLO)*(PLO+PUP)*HALF/CM
GO TO 15
C SPECIAL CASES INVOLVING ONE OR BOTH END POINTS
50 IF(XUP.LE.ZERO.OR.XLO.GE.PEMAX) RETURN
IF(XLO.LT.ZERO) XLO=ZERO
IF(XUP.GT.PEMAX) XUP=PEMAX
IBELO=XLO/DM
ILAST=XUP/DM
JCASE=1
IF(ILAST.GT.0) JCASE=JCASE+1
IF(ILAST.EQ.IEMAX) JCASE=JCASE+1
IF(IBELO.GT.0) JCASE=JCASE+1
IF(IBELO.EQ.IEMAX) JCASE=JCASE+1
GO TO (101,102,102,104,105),JCASE
101 GWHNRG=(XUP-XLO)*GWHPER/DM
RETURN
102 SUM=ONE-XLC/DM
XLO=DM
IBELO=1
IF(JCASE.EQ.2) GO TO 5
104 XO=IEMAX*DM
PUP=PROB(IEMAX)*(ONE-(XUP-XO)/(PEMAX-XO))
SUM=SUM+(XUP-XO)*HALF*(PUP+PROB(IEMAX))/DM
XUP = XO
ILAST = IEMAX - 1
GO TO 5
105 XO = IEMAX * DM
PUP = PROB(IEMAX) * (ONE - (XUP - XO) / (PEMAX - XO))
PLC = PROB(IEMAX) * (ONE - (XLO - XO) / (PEMAX - XO))
GWHNRG = (XUP - XLO) * (PLO + PUP) * HALF * GWHPER / DM
RETURN
END
SUBROUTINE ADDPLT(MWP)
C
C SY SINT VERSION 1-01-73
C ADDS PLANT OF MW MEGAWATTS AND P FRACTIONAL AVAILABILITY TO PROB,
C THE EQUIVALENT LOAD CDF
C NOTE: MW MUST BE LESS THAN OR EQUAL TO PEMIN
C ************************************************************
C IMPLICIT REAL*8 (A-H,O-$)
C COMMON VARIABLES
C OTHER VARIABLES COMMON TO SEVERAL SUBROUTINES
COMMON/PROB/DM,DT,GWHPER,DAYS,IEMIN,IEMAX,PEMIN,PEMAX,PROB(500)
COMMON/FLOAT/EPS,TRACE,PKMW,SPNRES,CSTEMR
COMMON/MAXIMUM/IDIMEN,MAXPLT,MAXPER,MAXNPT
COMMON/CONSTS/ZERO,ONE,TWO,HALF, TENTH,HUNDRD,CENTI,THOUS,MILLI
REAL*8 MILLI
C END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES
IF(MW.LE.0) RETURN
IF(MW.LE.PEMIN) GO TO 5
CALL ERRMSG('ADDPLT',2)
RETURN
5 TEMP = PEMAX
PRTEMP = PROB(IEMAX)
IDUX = IEMAX
IDUM = IEMAX + 1
Q = CNE - P
FB = MW/DM
INT = FB
FB = FB - INT
C CALCULATE NEW VALUES AT POINTS ON UPPER END OF PROB AND
C FIND NEW PEmAX AND IEMAX
PEMAX=PEMAX+MW
IEMAX=PEMAX/DM
DO 20 J=IDUX,IEMAX
   JINT=J-INT
   IF(JINT.EQ.IDUM) GO TO 10
   PRJINT=PROB(JINT)
   IF(JINT.EQ.IDUX) PRJINT=PRTEMP
   PROB(J)=PROB(J)+Q*(PRJINT-PROB(J)+FB*(PROB(JINT-1)-PRJINT))
   GO TO 15
10  PROB(J)=Q*PRTEMP*(TEMP/DM-IDUM+FB)/(TEMP/DM-IDUM+ONE)
15  IF(J.LT.IEMAX) PROB(J+1)=ZERO
    IF(PROB(J).LE.TRACE) GO TO 30
20  CONTINUE
    TEMP=IEMAX*DM+EPS
    IF(TEMP.GT.PEMAX) PEMAX=TEMP
    GO TO 40
30  PROB(J)=ZERO
    IEMAX=J
    PEMAX=IEMAX*DM+EPS
40  IF(IEMAX.GT.IDIMEN) CALL ERRMSG(*ADDPT*,1)
    J=IDUX
    JINT=J-INT
C LOOP TO CONVOLVE IN NEW PLANT
50  J=J-1
    IF(J.LE.IEMIN) RETURN
    JINT=JINT-1
    PROB(J)=PROB(J) +
$ Q*(PROB(JINT)-PROB(J)+FB*(PROB(JINT-1)-PROB(JINT)))
    GO TO 50
END
FUNCTION PROBX(X)
C SYSINT VERSION 10-15-71
C EVALUATES PROB AT A PARTICULAR VALUE OF X MW
C
C ********************************************
COMMON VARIABLES
IMPLICIT REAL*8 (A-H,O-$)

OTHER VARIABLES COMMON TO SEVERAL SUBROUTINES
COMMON/PROB/DM, DT, GWHPER, DAYS, IEMIN, IEMAX, Pemin, Pemax, PROB(500)
COMMON/CONSTS/ZERO, ONE, TWO, HALF, TEN, TENTH, HUNDRED, CENTI, THOUS, MILLI
REAL*8 MILLI

END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES

FUNCTION SUSDNO(AVBSLF)

SYSINT VERSION 10-15-71

APPROXIMATES NUMBER OF STARTUPS AND SHUTDOWNS DURING THE PERIOD
AS A FUNCTION OF THE AVAILABILITY-BASED LOAD FACTOR, AVBSLF

IMPLICIT REAL*8 (A-H,O-$)

OTHER VARIABLES COMMON TO SEVERAL SUBROUTINES
COMMON/PROB/DM, DT, GWHPER, DAYS, IEMIN, IEMAX, Pemin, Pemax, PROB(500)
COMMON/CONSTS/ZERO, ONE, TWO, HALF, TEN, TENTH, HUNDRED, CENTI, THOUS, MILLI
REAL*8 MILLI

END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES

IF(AVBSLF.GE.ONE) AVBSLF=ONE-1.D-1C
FB=20.D0
DO(AVBSLF)
ILO=FB
FB=FB-ILO
IF(ILO.GE.IEMAX) RETURN
FB=PROB(ILO)+FB*(PROB(ILO+1)-PRCB(ILO))
RETURN
10 PROBX=PROB(IEMAX)*(PEMAX-X)/(PEMAX-IEMAX*DM)
RETURN
END
FB = FB - ILO
IF (AVBSLF .LT. 0.05D0) GO TO 10
SUSDNO = DAYS * (F(ILO) + FB * (F(ILO+1) - F(ILO)))
RETURN
10  SUSDNO = DAYS * FB * F(1)
RETURN
END
SUBROUTINE PUNCHR(MODE)
C SYSINT
VERSION 11-2-71
C
PERFORMS PUNCHING OPERATIONS
C
NOTE THAT:
C 1. FOR PROGRAMMING MODULARITY, THIS SUBROUTINE PERFORMS PUNCHING
OF OUTPUT, WHETHER ON CARDS, TAPE OR DIRECT ACCESS DEVICE.
THE ONLY EXCEPTION IS THE FINAL TOTALS NAMELIST /FNLTOT/
PUNCHE BY THE SYSGEN SUBROUTINE.
C 2. THIS SUBROUTINE IS DEPENDENT UPON THE IBM/360 UTILITY PROGRAM
"IEBUPDTE" (RELEASE 20).
C
*********************************************************************
IMPLICIT REAL*8 (A-H,O-$)
C COMMON VARIABLES
C VARIABLES DIMENSIONED IN MULTIPLES OF MAXPLT, MAX. NO. OF STATIONS
COMMON/PLTDAT/IDNO(100),NAME(100),TYPE(100),SUSDHT(100),PNCM(100),
$NPTS(100),MWPT(5,100),HTRAT(5,100)
COMMON/PERDAT/AVLBTY(100),CSTBTU(100),STATUS(100),EXPHRS(100),
$EXPBTU(100),EXPGWHR(100),NORDER(500),COST(100),ENERGY(100),
$SUPCST(100),MRGCST(5,100)
C
OTHER VARIABLES COMMON TO SEVERAL SUBROUTINES
COMMON/PROB/DM,DT,GWPER,DAYS,IEMIN,IEMAX,PMIN,PMAX,PROB(500)
COMMON/FLOAT/DBS,TRACE,PKM,SPNRES,CTEQR
COMMON/TITLE/SGTITL(10),PDITITL(10)
COMMON/INTGR/RD,WT,PUNCH,CARD,TAPE,ERRCOD,NSTNS,NPER,NPERS,NPER1
$NPST,RCH,PCHMIN,PCHMAX,MBRNUM
COMMON/LDGNO/LDTYPE,LDTPS,LOAD(50,25),NORDOP,NOENTRY,NOBASE,
$NOPEAK,NNORD
COMMON/CONSTS/ZERO,ONE, TWO, HALF, TEN, TENTH, HUNDRED, CENTI, THOUS, MILLI
COMMON/LOGICL/MINI, MIDI, MAXI, NPM, PCHING
COMMON/MAINT/MAINT(100, 20)

C MAINT IS DIMENSIONED (MAXPLT, MAXPER/5) THE 5 IS 5!1/INTEGER*2
REAL*4 SUSDHT, PNM, HTRAT
REAL*4 SUPCST, MRGCST
REAL*8 MILLI
INTEGER RD, HT, PUNCH, CARD, TAPE, ERRCOD, PCHMIN, PCHMAX
INTEGER*2 IDNO, TYPE, NPTS, MWPT, NORDER, STATUS, MAINT, LOAD
LOGICAL*1 MIN1, MIDIMAX, INPMP, PCHING

C END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES
INTEGER*2 NTEST(100), NDXS(100), $N$/'N'/, LSTMOD/0/

C NTEST & NDXS DIMENSIONED MAXPLT
REAL*4 A(5)
IF (.NOT. PCHING) RETURN
MOD = MODE
IF (MOD .LE. 6) GO TO 10
IF (LSTMOD .NE. 2 .AND. LSTMOD .NE. 3) GO TO 10
MW = MODE
MOD = LSTMOD + 1
10 GO TO (100, 200, 300, 400, 500, 600), MOD

C STRATEGY INFORMATION
100 NUKES = 0
DO 110 N = 1, NOSTNS
   IF (TYPE(N).NE.$N$/'N'/) GO TO 110
   NUKES = NUKES + 1
   NDXS(NUKES) = N
110 CONTINUE
   IF (NUKES .GT. 0) GO TO 130

C SINCE NO NUKES, PUNCH ALL PLANTS
DO 120 N = 1, NOSTNS
   NDXS(N) = N
   NUKES = NOSTNS
   NPM = .FALSE.
120 CONTINUE

C JMAINT = (NPERS + 4)/5
CALL WHEN(A)
CALL DAYTIM
N=1
IPLACE=MBRNUM/1000000
WRITE(PUNCH,911) NPM,MBRNUM,N,NPM,MBRNUM,A
WRITE(PUNCH,912) NPM,IPLACE,IDSTRG,SGTITL,NUKES
WRITE(PUNCH,913) (IDNO(NDXS(I)),NAME(NDXS(I)),MWPT(1,NDXS(I)),
$MWPT(NPTS(NDXS(I)),NDXS(I)),NDXS(I),I=1,NUKES)
WRITE(PUNCH,914) NPERS,JMAINT
DO 140 N=1,NUKES
140 WRITE(PUNCH,915) (MAINT(NDXS(N),J),J=1,JMAINT)
GO TO 800
C PERIOD INFORMATION
C N.P.M. CHECK OF NORDER AND SET PCHMIN AND PCHMAX
200 PCHMIN=-1
PCHMAX=-1
IF(.NOT.NPM) GO TO 260
NSUM=0
MSUM=0
DO 210 NK=1,NUKES
N=nk=1,NUKES
NDX=NDXS(NK)
NTEST(NK)=1000*NPTS(NDX)+NDX
IF(STATUS(NDX).NE.2) GO TO 210
IF(NTEST(NK).GT.2000) NSUM=NSUM+NTEST(NK)
MSUM=MSUM+1000+NDX
210 CONTINUE
NPMFAL=0
NPMDEL=0
DO 220 J=1,NNORD
N=NORDER(J)
IF(N.GT.2000) GO TO 230
IF(TYPE(N-1000).EQ.$N$) MSUM=MSUM-N
220 CONTINUE
230 JLOW=J
J=J-1
IF(MSUM.NE.0) NPMFAL=100
IF(NSUM.EQ.0) GO TO 250
DO 240 J=JLCW,NNORD
N=NORDER(J)
M=N-(N/1000)*1000
IF(TYPE(M).NE.SNS) NPMDEL=20
DO 240 NK=1,NUKES
IF(N.EQ.NTEST(NK)) NSUM=NSUM-TEST(NK)
IF(NSUM.EQ.0) GO TO 250
240 CONTINUE
CALL ERRMSG('PUNCHR',9)
250 PCHMAX=J
PCHMIN=JLOW-1
NPMFAL=NPMFAL+NPMDL
IF(NPMFAL.EQ.0) GO TO 260
WRITE(WT,921) NPMFAL
CALL ERRMSG('PUNCHR',11)
260 WRITE(PUNCH,922) NPER,A,PDTITL,NPER,DM,DT,CSTEMR
IF(.NOT.NPM) MOD=4
GO TO 800
C PROB AT NUCLEAR MINIMUMS
300 M=MW
NTBSLD=0
DO 310 NK=1,NUKES
N=NDXS(NK)
IF(EXPHRS(N)+MILLI.LT.DT*CENTI*AVLBTY(N)) NTBSLD=NTBSLD+1
310 M=M+MWPTNPTS(N),N)-MWPT(1,N)
LPTS=MAXO,IDINT(M/DM)-IEMIN+2,1)
LPTS=MNO(LPTS,IEMAX-IEMIN)
IF(NTBSLD.EQ.0.0.0.0.MW.LE.PEMIN) GO TO 320
NPMFAL=NPMFAL+3
WRITE(WT,932) NPMFAL,NTBSLD,(EXPHRS(NDXS(NK)),NK=1,NUKES)
CALL ERRMSG('PUNCHR',12)
320 WRITE(PUNCH,931) MW,IEMIN,LPTS,(PROB(IEMIN+1),I=1,LPTS)
WRITE(PUNCH,933) NPMFAL,NTBSLD,(EXPHRS(NDXS(NK)),NK=1,NUKES)
GO TO 800
C PROB AT NUCLEAR MAXIMUMS
400 LPTS=MAXO(IDINT(MW/DM)-IEMIN+2,1)
LPTS=MINO(LPTS,IEMAX-IEMIN)
WRITE(PUNCH,941) MW,IEMIN,LPTS,(PRCB(IEMIN+I),I=1,LPTS)
GO TO 800
C
FINAL PERIOD RESULTS
C
NOTE SUBROUTINE SYSGEN HAS ALREADY PUNCHED THE FINAL TOTALS
C
500 WRITE(PUNCH,951) (CSTBTU(NDXS(I)),AVLBTY(NDXS(I)),ENERGY(NDXS(I)),
$EXPHTS(NDXS(I)),EXPGWH(NDXS(I)),EXPBTU(NDXS(I)),COST(NDXS(I)),
$I=1,NUKES)
MOD=1
IF(NPER.LT.NPERS) GO TO 800
WRITE(PUNCH,952) NPM,MBRNUM,A
GO TO 700
C
ABORT CAUSED BY DETECTION OF SEVERE ERROR
600 IF(LSTMOD.GT.0) WRITE(PUNCH,961)NPM,MBRNUM,A
PUNCH=PUNCH-1000
PCHING=.FALSE.
700 LSTMOD=0
RETURN
800 LSTMOD=MOD
RETURN
911 FORMAT(/'ADD NAME='*,L1,I7,'LEVEL='*,Z2,'LIST=ALL'/
$'--------BEGIN STRATEGY WITH NAME='*,L1,I7,' ON '*,2A4,' AT '*,
$3A4,'--------'/)
912 FORMAT(L3,I3,I6,10A7/15)
913 FORMAT(I5,A5,2I5,1I0)
914 FORMAT(NUKES'' MAINT.DATA FOR',T22,I4,' PERIODS ('*,T41,I3,
$' VALUES)'/)
915 FORMAT(1615)
921 FORMAT('ONPMFAL=',I3,4X,'(100=FIRST REASON, 20=SECCND REASON,,'
$ OR 120=BOTH REASONS FOR ERROR 11 (HEXADECIMAL 8)')
922 FORMAT(13(''''),I3,'TH PERIOD TO FOLLOW SIMULATED ''*,5A4,13('''/)
$10A8/110,3F10.4)
931 FORMAT('MIN '',3I5,6F10.9/(8F10.9))
932 FORMAT('ONPMFAL=',I3,6X,'NTBSLD='*,I3/)
SUBROUTINE ERRMSG(SUBR, JERR)
C SYSINT VERSION 1-01-73
C WRITES OUT ALL ERROR MESSAGES
C **********************************************************************
C IMPLICIT REAL*8 (A-H,O-$)
C COMMON VARIABLES
C OTHER VARIABLES COMMON TO SEVERAL SUBROUTINES
COMMON/INTEGR/RD,WT,PUNCH,CARD,TAPE,ERRCOD,NOSTNS,NPER,NPERS,NPERI
$ IDSTRG, PCHMIN, PCHMAX, MBRNUM
INTEGER RD, WT, PUNCH, CARD, TAPE, EErrCOD, PCHMIN, PCHMAX
C END OF STATEMENTS COMMON TO SEVERAL SUBROUTINES
DATA NPRINT/0/$QUIT$/' QUIT'/
IERR=JERR
100 EErrCOD=16*ERRCOD+IERR
IF(ERRCOD.GT.8*16**6) IERR=8
NPRINT=NPRINT+1
GO TO (1,2,3,4,5,6,7,8,9,10,11,12),IERR
1 WRITE(WT,901) SUBR, EErrCOD, NPRINT
GO TO 1000
2 WRITE(WT,902) SUBR, EErrCOD, NPRINT
GO TO 1000
3 WRITE(WT,903) SUBR, EErrCOD, NPRINT
RETURN
4 WRITE(WT,904) SUBR, EErrCOD, NPRINT
GO TO 1000
5 WRITE(WT,905) SUBR,ERRCOD,NPRINT
RETURN
6 WRITE(WT,906) SUBR,ERRCOD,NPRINT
GO TO 1000
7 WRITE(WT,907) SUBR,ERRCOD,NPRINT
GO TO 1000
8 WRITE(WT,908) SUBR,ERRCOD,NPRINT,NPRINT
STOP
9 WRITE(WT,909) SUBR,ERRCOD,NPRINT
GO TO 1000
10 WRITE(WT,910) SUBR,ERRCOD,NPRINT
IERR=8
GO TO 100
11 WRITE(WT,911) SUBR,ERRCOD,NPRINT
RETURN
12 WRITE(WT,912) SUBR,ERRCOD,NPRINT
RETURN
1000 NPRINT=NPRINT+1
WRITE(WT,999) NPRINT
CALL QUIT
SUBR=$QUIT
IERR=10
GO TO 100
901 FORMAT(/I',130('*')/,'* SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
'$ IEMAX GREATER THAN DIMENSION OF PROB ARRAY ',
$T131, '*',/,' ',130('**'),I2)
$T131,***/','130('**'),I2$

905 FORMAT(/',130('**)/,'* SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
$* WARNING : ERROR IN EXPECTED MW OUTAGES GREATER',
$* THAN 0.01% ',
$T131,***/','130('**'),I2$

906 FORMAT(/',130('**)/,'* SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
$* INPUT DECK HAS IMPROPER SEQUENCE &/OR CARD ',
$T131,***/','130('**'),I2$

907 FORMAT(/',130('**)/,'* SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
$* INVALID OR INCONSISTENT IDNO ENCOUNTERED ',
$T131,***/','130('**'),I2$

908 FORMAT(/',130('**)/,'* SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
$* SUPSIM ENCOUNTERED STOP CARD, ERRMSG CALLED ONCE TOO OFTEN OR 0',
$* OTHER FATAL ERROR', T131,***/ * DURING THIS ENTIRE RUN, ERRMSG',
$* PRINTED A TOTAL OF ',I3,' ERROR MESSAGES JUST LIKE (AND ',
$* INCLUDING) THIS ONE',
$T131,***/','130('**'),I2$

909 FORMAT(/',130('**)/,'* SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
$* INPUT NORDER ERROR SUCH AS TOO FEW/MANY VALVE',
$* POINTS, BAD IDNO OR UNLISTED ON-LINE PLANT',
$T131,***/','130('**'),I2$

910 FORMAT(/',130('**)/,'* SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
$* "QUIT" EXECUTED A RETURN TO "ERRMSG" ',
$T131,***/','130('**'),I2$

911 FORMAT(/',130('**)/,'* SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
$* BASE NUCL. W/IN NUCL. NON-MINIMUMS OR NON-MIN',
$* INPUT NON-NUCL. V.PTS. PRECEDE SOME NUCL. V.PTS.',
$T131,***/','130('**'),I2$

912 FORMAT(/',130('**)/,'* SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
$* MINIMUM LOAD TOO LOW TO KEEP NUKE ON ALL THE TIME',
$T131,***/','130('**'),I2$

999 FORMAT/','130('**)/,'* PREVIOUS ERROR SEVERE ENOUGH TO',
$* INVALIDATE FURTHER COMPUTATIONS. THEREFORE, RETURNING',
$* CCNTROL TC SUPSIM',
$T131,***/','130('**'),I2$

END
SUBROUTINE CMPTIM(LVENT)

C SYSINT VERSION 10-15-71
C PRINTS TIME OF INTRA-SUBROUTINE TRANSFERS OR DATE/TIME
C "TIMING" IS AN M.I.T. INTERNAL SUBROUTINE THAT RETURNS THE CPU TIME
C IN HUNDREDTHS OF SECONDS.
C "WHEN" IS AN M.I.T. INTERNAL SUBROUTINE THAT RETURNS THE DATE AND
C TIME IN THE FOLLOWING 5A4 FORMAT: MM/DD/YY HR*MI*SS.FF
COMMNT/INTEGR/RDWT
INTEGER RDWT
DIMENSION A(5)
DOUBLE PRECISION LVENT
INTEGER TNOW,TSTART,TREL
CALL TIMING(TNOW)
TREL=TNOW-TSTART
IF(TREL.LT.0) TREL=TREL+8640000
TI=TREL/100.
WRITE(WT,10)LVENTTI
RETURN
ENTRY STRTIM
CALL TIMING(TSTART)
ENTRY DAYTIM
CALL WHEN(A)
WRITE(WT,20)A
RETURN
10 FORMAT(/,T103,29('*'),/,,T103,'* LV. ',A6,T131,'*',/,
      $T103,'* ENT. ',A6,' @',F7.2,' SEC. '*',/,,T103,29('**'),/)
20 FORMAT(/T103,29('**')/T103,'* DATE = ',2A4,T131,'**'/
      $T103,'* TIME = ',3A4,T131,'**'/T103,29('**')/)
END

**************************************************************************
* ASSEMBLER LANGUAGE SUBROUTINE ERASE
* WRITTEN BY JOHN W. KIDSON
* MIT DEPARTMENT OF METEOROLOGY
* TO SET ELEMENTS OF REAL OR INTEGER ARRAYS TO ZERO. A1,A2,... *
**************************************************************************
** ARE ARRAY NAMES AND N1, N2, ... ARE INTEGER VALUES OR **
** EXPRESSIONS GIVING THE ARRAY SIZES. **
** I.E. - CALL ERASE(C, 26*31, N, 7*31, E, 254) **
** * **

**************************************************************************************
START 0
SAVE (14,12), *
BALR 12, 0
USING *, 12
SR 0, 0
SR 2, 2
SLA 7, 2
SR 7, 6
SR 5, 5
ST 0, 0
BXLE 5, 6, E2
LTR 4, 4
BM RETN
A 2, =F'8'
B E1
RETNSAVE (14,12), T
END
**************************************************************************************
**AN ELECTRIC UTILITY SYSTEM OPTIMIZATION MODEL**

**WRITTEN BY PALL F. DEATON**

**M.I.T. DOCTORAL THESIS, MARCH 1973**

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**SYSOPT MAIN PROGRAM**

**SYSOPT VERSION 12-16-72**

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**DEFINITIONS OF IMPORTANT VARIABLES**

- **$NKPRD**: DIRECT NUCLEAR PRODUCTION FUEL COST \((10^{12} \text{ $})\)
- **$NKSUS**: NUCLEAR STARTUP & SHUTDOWN COST \((10^{12} \text{ $})\)
- **$NKTCT**: TOTAL COST OF NUCLEAR PRODUCTION \(= NKPRD + NKSUS \ (10^{12} \text{ $})\)
- **$PNS$:**: NON-NUCL. PRODUCTION FUEL COST \((10^{12} \text{ $})\)
- **$NNSUS**: NON-NUCL. STARTUP & SHUTDOWN COST \((10^{12} \text{ $})\)
- **$SBT**: TOTAL COST OF PRODUCTION \((10^{12} \text{ $})\)
- **AVL**: LINEAR SOLUTION VARIANCE PARAMETER (PER GWHE)
- **AVL**: REACTOR PERFORMANCE PROBABILITY (PER CENT)
- **AVL**: BASED CAP. FACTOR FOR REACTOR BASE PORTION (%)
- **AVL**: BASE VARIANCE FOR SOLUTION COMPARISON
- **AVL**: CONSTANT SOLUTION VARIANCE PARAMETER
- **AVL**: AVERAGE C.D.F. VALUE FOR PERIOD
- **AVL**: AVERAGE C.D.F.
- **AVL**: C.D.F. AT LVLMAX
- **AVL**: C.D.F. AT LVLMIN
- **AVL**: OPTIMUM IN-CORE DETAIL PRINT OPTION \((0= \text{ ND}, 1= \text{ YES})\)
- **AVL**: CUMULATIVE CYCLE NUMBER FOR GIVEN R-C
- **AVL**: MAXIMUM R-C FOR REACTOR
- **AVL**: RANGE OF PERIODS COVERED BY EACH R-C
- **AVL**: NUMBER OF EXCESS CYCLES BEYOND CRISIS OF INTEREST
- **AVL**: DELTA CAPACITY FACTOR LIMITS \(= \text{ SQRT}(- \text{SLNCRT})\)
- **AVL**: DMW
- **AVL**: EQUIVALENT LCAD STEP SIZE (MW)
- **AVL**: DTH
- **AVL**: PERIOD DURATION (HOURS)
C CYCWN = COWN TIME FOR EXCESS CYCLE (YEARS)
C CYHOLD = POST-HORIZON TIME UNTIL END OF SPLIT CYCLE (YEARS)
C CYUP = UP TIME FOR EXCESS CYCLE (YEARS)
C ECS = EMERGENCY POWER COST ($/MWHE)
C ECUPLM = UPPER LIMIT CN EC'S IMPOSED BY IN-CORE MODEL (GWHE)
C ELAME = SANDWICHED TABLE OF EC'S, LAMBCAS & EC'S (GWHE,$/MWHE)
C EMRP$ = COST OF EMERGENCY POWER PURCHASES (10**3 $)
C EXPCEM = EXP. CUSTOMER ENERGY DEMAND (GWHE)
C EXPEMR = EXP. EMERGENCY ENERGY PURCHASED (GWHE)
C EXPGEN = EXP. UTILITY TOTAL GENERATION (GWHE)
C EXPGWH = SYSINT EXPECTED GENERATION BY EACH REACTOR (GWHE)
C FINST = FINE-GRAINED SHAPE TEST FOR THE PERIOD
C FINTST = FINE-GRAINED SHAPE TEST FOR THE PERIOD
C GESFRS = FIRST GUESS OPTION(0=NONE,1=SYSINT,2=MRGCST,3=CA.EC,4=EC)
C CMESH = INCREMENTAL SPACING USED FOR ARC TYPES 2 & 3 (GWHE)
C GWHOLD = GWHE HELD OVER FOR LATER PRODUCTION IN SPLIT CYCLE
C CWFPER = GWHE PER UNIT OM UNDER CDF
C CWFXS = EC FOR EXCESS CYCLE (GWHE)
C IIAUX = TOTAL NUMBER OF ARCS TO AUXILIARY R-C NODE
C IIAUXM = IIAUX-1
C IDNC = REACTOR I.D. NUMBER
C IDSTRG = STRATEGY I.D. NUMBER
C IEMAX = PEMAX/DM
C IEMIN = PEMIN/DM
C INSTAT = INITIAL STATE OF REACTOR AT START OF PERIOD 1 (CF. 'S')
C ITER = INNER COST ITERATION NUMBER
C JFRPBK = JFRWRD + JBKWRD
C JFRWBD = NUMBER OF FORWARD ARCS OF TYPE 7
C JFPRB = JFRWRD + JBKWRD
C KC = UNIT TRANSPORTATION COST ACROSS ARC ($/GWHE)
C KL = ARC CAPACITY LOWER LIMIT (GWHE)
C KU = ARC CAPACITY UPPER LIMIT (GWHE)
C KX = ARC CAPACITY USED (GWHE)
C LVLMIN = LVLMN
C LVLMAX = LVLMX
POWER LEVEL AT END OF MAXIMUMS

REACTOR-TO-PERIOD MAX. GWHE CONTRIBUTION TO NUCL. POTENTIAL

MAXIMUM POSSIBLE SHAPE TEST FOR THE PERIOD

MAXIMUM POSSIBLE VARIANCE FOR THE PERIOD

SEQUENCE OF GMESH VALUES TO BE USED IN CONVERGENCE (GWHE)

REACTOR IN MID-CYCLE AT START OF PERIOD 1?

INCREMENT OF CAPACITY AVAILABLE FOR LOAD FOLLOWING (MW)

UTILITY INSTALLED CAPACITY (MW)

REACTOR MAXIMUM LOAD (MW)

REACTOR MINIMUM LOAD (MW)

ON-LINE CAPACITY MARGIN ABOVE FORECAST PEAK (MW)

UTILITY ON-LINE CAPACITY (MW)

FORECAST PEAK CUSTOMER DEMAND (MW)

SPinning RESERVE REQUIREMENT (MW)

MAXIMUM ALLOWED NUMBER OF ARCS IN O-C-K

FIRST DIMENSION OF ELAME = (MAX. NO. EC'S IN COL.) * 2

MAXIMUM ITERATIONS TO BE ATTEMPTED

MAXIMUM ALLOWED NUMBER OF NODES IN O-C-K

MAXIMUM ALLOWED NUMBER OF PERIODS IN SYSOPT STUDY

MAXIMUM ALLOWED CYCLES FOR A SINGLE REACTOR

CUMULATIVE NUMBER OF R-C'S

NUMBER OF MESHES TO BE READ IN

PERIOD INDEX

NUMBER OF PERIODS IN SYSINT SIMULATION OUTPUT

NUMBER OF CYCLES COMPRISING TIME HORIZON OF INTEREST

COMPUTER DEVICE NUMBER FOR NET.PROG. INPUT

NUCLEAR POWER MANAGEMENT STUDY?

SYSINT ERROR INDICATION THAT SYSOPT N.P.M. MAY FAIL

COMPUTER DEVICE NUMBER FOR NET.PROG. OUTPUT

REACTOR INDEX

NUMBER OF REACTORS IN THE STRATEGY

NUMBER OF REACTORS NOT BASE-LOADED IN THE PERIOD

SYSINT OPERATING HOURS FOR REACTOR
C  CPRCCR = IN-CORE PRINT OPTIONS TO BE USED FOR OPTIMUM SOLUTION
C  PAPCAL = ARC TYPES PRINTED FOR ALL 0-O-K SOLUTIONS
C  PARCON = ARC TYPES PRINTED FOR CONVERGED 0-O-K SOLUTIONS
C  PARCOP = ARC TYPES PRINTED FOR OPTIMUM 0-C-K SOLUTION
C  PCCNVG = PER CENT GMESH USED FOR CONVERGENCE TEST
C  PCDLA = PERIOD CAP. FACT. RANGE CORRECTION (PER CENT DELTAL)
C  PCDELIM = PERIOD DELIMITING CARD
C  PRTITLE = PERIOD TITLE CARD
C  PNAME = MAXIMUM EQUIVALENT LOAD CONSIDERED (MW)
C  PEMAX = MINIMUM EQUIVALENT LOAD (MW)
C  PCFL = PROBABILITY OF LOSS OF LOAD (FRACTION)
C  PROB = CUMULATIVE DENSITY FUNCTION (C.C.F.) FOR EQUIVALENT LOAD
C  PDIR = DIRECT PRODUCTION FUEL COST (10**3 $)
C  FVFACT = MID-PERIOD PRESENT VALUE FACTOR (FRACTION)
C  PVRATE = PRESENT VALUE RATE (FRACTION PER YEAR)
C  REJLVL = REJECTION LEVEL FOR FINVAR-SLNSR
C  $  = REACTOR STATUS DURING PERIOD (0=NONE, 1=DOWN, 2=UP)
C  SGTITLE = STRATEGY TITLE
C  SCT = COMPUTER DEVICE NUMBER FOR SYSINT OUTPUT
C  SLMCRT = SOLUTION SHAPE CRITERION = FINVAR-SLNSR-REJLVL (.GE.0)
C  SLNSR = SOLUTION WTD. SUM OF SQUARES OF RESIDUALS (THEISIS W**2)
C  SPE = PRESENT VALUE SUMS OF VARIOUS PERIOD COSTS
C  SUSDC = SYSTEM STARTUP & SHUTDOWN COST (10**3 $)
C  TSE = TIME AT END OF CYCLE (YEARS)
C  TH$CON = CONVERGENCE CRITERION ON SYSTEM NUCLEAR CCST (10**3 $)
C  TOAL$ = TOTAL SYSTEM COST = $NKTOT + $NNTO + EMRP$ (10**3 $)
C  TOY = OPERATING TIME OF CYCLE (YEARS)
C  TST = TIME AT START OF CYCLE (YEARS)
C  LNSRWD = SECOND ESTIMATE OF UNSERVED ENERGY, EXPEMR (GWHE)
C  WRT = COMPUTER DEVICE NUMBER FOR PRINTER
C  XAKGEN = EXP. NUCLEAR GENERATION (GWHE)
C  XNNGEN = EXP. NON-NUCL. GENERATION (GWHE)
C  YBASE = BASE YEAR FOR PRESENT VALUING
C YEND = END POINT OF PERIOD (YEARS)
C YMID = MID-POINT OF PERIOD (YEARS)
C YSTART = YEAR OF START OF FIRST PERIOD IN THE STRATEGY
C*************************************************************************
C END OF DEFINITIONS **********************************************************
IMPLICIT INTEGER(C,G)
REAL*8 RFACTSGTIL
CCMMCN/OPTLIM/RDFACT,SGTILT(10),ELAME(40,18),PVRATE,YBASE,YSTART,
$IAUX,IAUXM,NCRCS,NCYCT,NPER,NPERS,NPERSP,NPERIN,ITER,MXESX2,MXRCYC,
$MXNPER,MXRCS,MAXD,MXARC,SIOT,NPCT,RD,WT,PARCAL,PARCON,
$PARCOP,PCCNVG,NPM,ICSTRG,JFRWRD,JBKWRD,NMESH,MESM(15),MXITER
$,GESFRS,ECUPLM(18),CORDTL,OPRSCOR(6),REJLVL,PCDELA,TH$CON,JFRPBK
INTEGER SIOT,RC,WT,PARCAL,PARCON,PARCOP
LOGICAL $NKPRED
LOGICAL OPTRCH,SHPSOK
REAL*3 $NKPRD
DIMENSION X(20)
CATA $STOP$, $STRA$, $NEWB$, $COMP$/'STOP','STRA',NEW',COMP' /
WRITE(WT,903)
WRITE(WT,900)
10 CALL STRTIM(WT)
20 READ(RD,501) X
WRITE(WT,902)X
IF(X(1).EQ.$STOP$) CALL CPERR('SYSOPT',8)
IF(X(1).EQ.$STRA$) GC TO 30
IF(X(1).EQ.$COMP$) GO TO 40
IF(X(1).EQ.$NEWB$) CALL CPERR('SYSOPT',6)
CALL CMPTIM('SYSOPT','INPU'T)
CALL ICNPUT
CALL CMPTIM('INPU'T','SYSOPT')
GO TO 20
30 CALL CMPTIM('','INPU'T')
CALL RDOPTN
CALL RDSRTG
X(1)=LOC(10,0,0,0)
CALL RDPER
CALL ASMTYS

PAGE 5
CALL WTPERS
CALL SETUPN
CALL SETLPT
GO TO 20

40 CALL CMPTIM('INPUT','CALCS')
$NKPRD=J, CDO

50 CALL CONVRG(OPTRCH,$NKPRC)
CALL CHKSHP(SHPSOK)
IF(ITER.LT.MXITER.AND.OPTRCH.AND..NOT.SHPSOK) GO TO 50
CALL EDTSHP(SHPSOK)
CALL OUTFMUM(CPTRCH,$NKPRC)
CALL CMPTIM('CALCS','')
IF(.TRUE.) GO TO 10

STOP

900 FORMAT(T31,72(' ')/T31,*'/T102,*'/T31,*'/T37,*' SY S O P T : 
$ AN ELECTRIC UTILITY SYSTEM OPTIMIZATION MODEL',T102,*'/
$T31,*'/T64,*'WRITTEN BY PAUL F. DEATON',T102,*'/
$T31,*'/T58,*'M.I.T. DOCTORAL THESIS, MARCH 1973 ',T102,*'/
$T31,*'/T102,*'/T31,72(*')//
$T56,'VERSION 12-16-72')

901 FORMAT(2CA4)

902 FORMAT('SYSOPT READ : ',1H',20A4,1H')

903 FORMAT('O'/0'/O'/0')

END

C C C C

C INITIALIZES COMMON BLOCKS AND DIMENSIONS O-O-K ARRAYS

C SYSOPT VERSION 12-16-72

C IMPLICIT INTEGER(C,G)

REAL*8 RFACT,SGTTL
COMMON/OPTLIM/RFACT,SGTTL(10),ELAME(40,18),PVRATE,YBASE,YSTART,
$IAUX,IAUXM,NRCS,NCYCT,NPERS,NPERSP,NPERIN,ITER,MXESX2,MXRCYC,
$MXPER,MXRCRS,MXNODS,MXARC,SJOT,NPIN,NPCT,RO,WT,PARCAL,PARCON,
$PARCOP,PCCONV,NPM,IDSTRG,JFRWRD,JBKWRD,NMESH,MESH(15),MXITER
$GESFRS,ECUPLM(18),CRTC,CPSCOR(6),REJLVL,PCDELA,TH$CON,JFRPBK
INTEGER SJOT,RO,WT,PARCAL,PARCON,PARCOP
LOGICAL NPM,CPSCOR

PAGE 6
LOGICAL MIDCYC
INTEGER*2 CYCNUM, CYCRNG, CYCXS, CYCRMX
COMMON/RCDAT/DYDWN(3,15), DYUP(3,15), GWHXS(3,15), CYCXS(15),
$CYCRMX(15), CYCNUM(18,15), CYCRNG(2,270), IDNO(15), GWHOLD(15), MWD(15)
$, TSY(18,15), TEY(18,15), INSTAT(15), MWMIN(15), MWMAX(15), MIDCYC(15)
$DYHOLD(15), TOY(18,15)
COMMON/DCCCM/K1X, K0X, KQ1X, KQ2X, KQ3X, KQ4X, KQ5X
COMMON /KL/KC/KL/KU/KX/NL/NN/NP/NP/ IJ/IJ/ IL/IL
COMMON /JL/JL/JI/JI
DIMENSION KL(3500), KC(3500), KU(3500), KX(3500), NL(70)
DIMENSION NN(1400), NP(700), NL(701), JL(701), JI(3500)
COMMON/PDPERM/S(100,15), ALPHA(100,15), BETAP(100,15), FINVAR(100)
INTEGER$2 S
COMMON/PTEMP/NPMFAL(100), NTBSLD(100), OPFRS(100,15), LVLMN(100),
$S(LVLX(100), PDELIM(20,100), PDTITL(20,100), CMW(100), DTH(100), ECS(100
$), R4(13,100), R8(12,100), VMD(100), YEND(100), PWF(100), AVL(100,
$), EXPGWH(100,15), CAVG(100), BASVAR(100), FIN(100), MAXVAR(100),
$MAXST(100), MIN(100,15), MAX(100,15), BSCF(100,15,15)
REAL MAXVAR, MAXST, CAVG
REAL*8 PWF, R8
COMMON/PROB/PM, DM, DT, GWHPER, DAYS, IEMIN, IEMAX, PMIN, PMAX, PRBG(500)
$S(LVLX, LVLMAX
REAL*8 DM, DT, GWHPER, DAYS, PMIN, PMAX, PCE
COMMON/FINALS/S4, SA4, SP4, SL4, SP8
REAL*8 S4(13), SA4(13), SP4(13), SL4(13), SP8(13)
COMMON/PRINTS/RELCST, INCCST, BALCST, NBLCST, PIRDAT, PBATCS, KRD, KWT
LOGICAL RELCST, INCCST, BALCST, NBLCST, PIRDAT, PBATCS
COMMON/SHPIF/SLNCR(100), SLNWSR(100), ITFSHP, PDWBSD(100)
LOGICAL PDWBSD
CATA MXESX2/40/
CATA MXRNCYC/18/
CATA MXNPER/100/
CATA MXRCRS/15/
CATA MXRACS3500/
CATA MXNCCS700/
CATA RD/5/
READS IN DATA PERTINENT DIRECTLY TO SYSOPT
C
SYSOPT VERSION 12-16-72
IMPLICIT INTEGER(C,G)
REAL*3 RCFACT,SGTITL
COMMON/OPTLIM/RDFACT,SGTITL(10),ELAME(40,18),PVRATE,YBASE,YSTART,
,IAUX,IAUXM,NRCRS,NCYCT,NPERS,NPERSP,NPERIN,ITER,MXESX2,MXRCYC,
,MXPER,MXRCRS,MXNODS,MXARCS,SIOT,NPIN,NPCT,RT,WT,PARCAL,PARCON,
,FARCCP,PCONVG,NPM,IDSTRG,JFRWRD,JBKWRD,NMESH,MESH(15),MXITER
,S,GESFRS,ECUPLM(18),C RDTL,CP RCOR(6),REJLVL,PCDELA,TH$CON,JFRPBK
INTEGER SIOT,RTD,WT,PARCAL,PARCON,PARCOP
LOGICAL NPM,OPRCOR
LOGICAL MIDCYC
INTEGER*2 CYCNUM,CYCRNG,CYCX,CYCRMX
COMMON/RCDAT/DYDWN(3,15),DYUP(3,15),GWHXS(3,15),CYCXS(15),
,CYCRMX(15),CYCNUM(18,15),CYCRNG(2,270),ICNO(15),GWHOLD(15),MWD(15)
,T,TSY(18,15),TEY(18,15),INSTAT(15),MWMIN(15),MWMAX(15),M IDCYC(15)
,DYHOLD(15),TOY(18,15)
READ (RD,901) NPM,IDSTRG,NRCRS
WRITE (WT,911) NPM,IDSTRG,NRCRS
READ (RD,907) SIOT,NPIN,NPOT,PARCAL,PARCON,PARCOP,CORDTL,CPRCOR
WRITE (WT,912) SIOT,NPIN,NPOT,PARCAL,PARCON,PARCOP,CORDTL,OPRCOR
READ (RD,903) PVRATE,YBASE,YSTART,PCCNVG,TH$CCN,PCDELA,REJLVL,
,NPERS,GESFRS,MXITER,IAUX,JFRWRD,JBKWRD
CALL PVINIT(PVRATE)
WRITE (WT,913) PVRATE,YBASE,YSTART,PCCNVG,TH$CCN,PCDELA,REJLVL,
,NPERS,GESFRS,MXITER,IAUX,JFRWRD,JBKWRD
JFRPBK=JFRWRD+JBKWRD
IF (GESFRS-2) 20,5,12
WRITE (WT,916) (I,I=2,MXRCYC)
GO TO 10 NR=1,NRCRS
READ (RD,906) (ELAME(NR,1),I=1,MXRCYC)
WRITE (WT,917) NR,(ELAME(NR,1),I=1,MXRCYC)
GO TO 20

12 WRITE(WT,918) (I,I=2,MXRCYC)
   CO 15 NR=1,NRCRS
15 WRITE(WT,919) NR,(ELAME(NR,I),I=1,MXRCYC)
20 READ (RD,902) NMESH,(MESH(N),N=1,NMESH)
20 READ (RD,903) IDNO(NR),INSTAT(NR),CYCX2(NR),GWHOLD(NR),DYHOLD(NR),
   $(DYDWN(C,NR),DYUP(C,NR),GWHXS(C,NR),C=1,3),NR=1,NRCRS)
   WRITE(WT,915)NR,(ELAME(NRI),I=1,MXRCYC)
   WRITE(WT,914)NMESH,(MESH(N),N=1,NMESH)
   READ (RD,905) IDNO(NR),INSTA(NR),CYCX2(NR),GWHOLD(NR),DYHOLD(NR),
   $(DYDWN(C,NR),DYUP(C,NR),GWHXS(C,NR),C=1,3),NR=1,NRCRS)
   WRITE(WT,915)NR,(IDNO(NR),INSTAT(NR),CYCXS(NR),GWHOLD(NR),DYHOLD(NR),
   $(DYDWN(C,NR),DYUP(C,NR),GWHXS(C,NR),C=1,3),NR=1,NRCRS)
   IAUXM=IALX-1
   NPERSP=NPERS+1
   IF(NRCRS.GT.MXRCRS.OR.NPERS.GT.MXNPER.OR.IAUX.GT.(MXESX2/2-1).OR.
   $IAUX.LT.3.OR.JFRWRD.GT.6.OR.JFRWRD.LT.2.OR.JBKWRD.GT.5.OR.
   $JBKWRD.LT.1.OR.NPERS.GT.MPERS.OR.IDSTRG NRCRS'/9X,L1,7,16)
   CALL OPERR('RDOPTN',6)
   RETURN
901 FORMAT(L3,17,15)
902 FORMAT(1615)
903 FORMAT(6F7.0,F8.),615)
905 FORMAT((14,213,15,F7.4,3(2F6.4,1I))))
906 FORMAT(20F4.0)
907 FORMAT(715,6L1)
911 FORMAT('1',10X,'SYSOPT INPUT READ BY RDOPTN :/
   $(0 NPM IDSTRG ARCRS'9X,L1,17,16)
912 FORMAT('0 SIOT NPIN NPOT PARCAL PARCON PA
   $RCCP CCRD TL CPRCOR'/7110,6X,6L1)
913 FORMAT('0 PVRATE YBASE YSTART PCCNVG',
   $(0 THSNCN PCEL PCONPC REJLVL NPERS
   $GESFRS MXITER IAUX JFRWRD JGBKWRD'/F13.6,2F11.4,
   $(10.2,F8.3,F7.0,1PE10.1,6L10
914 FORMAT('ONMESH',9X,'MESH(1),I=1,NMESH'/I5,5X,2415)
915 FORMAT('0 NR IDNO INSTA CYCXS GWHOLD CYCXS',
   $(CYUP1 GWHXS1',6X,'CYDWN2 DYUP2 GWHXS2',6X,'CYDWN3 DYUP3 GW
   $+$XS2'/I5,216,19,19,FS.4,3(F13,4,F8.4,17))
916 FORMAT('0 INITIAL GUESS OF REACTOR-CYCLE MARGINAL COSTS :/
   $(0 NR RC: 1',(1717)/(4X,1817))
917 FORMAT(I4,3X,-3P18F7.3/(5X,-3P18F7.3))
918 FORMAT("0 INITIAL GUESS OF REACTOR-CYCLE ENERGIES, EC'"S ;/
$" NR RC: 1",(1717)/(4X,1817))
919 FORMAT(I4,3X,18F7.0/(5X,18F7.0))
END
SUBROUTINE RDSTRG
C READS STRATEGY INFC. CUTPUT BY SYSINT
C SYSOPT VERSION 12-16-72
IMPLICIT INTEGER(C,G)
REAL*8 RCFACT,SGTITL
COMMON/OPTL IM/RDFACT,SGTITL(10),ELAME(40,18),PVRAT E,YBASE,YSTART,
$IAUX,IAUXM,NCRS,NCYCT,NFEKS,NPERSP,NPERIN,ITER,MXESX2,MXRCYC,
$MNPER,MXRCRS,MXNODS,MXARCS,SIGT,NPIN,NPCT,RP,W,PARCAL,PARCNCN,
$PARCC,PCCNVG,NPM,ICSTRG,JFRWRD,JBKWRD,NMESH,MESH(15),MXITER
$GESFRS,ECUPLM(18),COPDTL,CPRCOR(6),REJLVL,PCDEL A,TH$CON,JFRPBK
INTEGER SIOT,RP,W,PARCAL,PARCNCN,PARCOP
LOGICAL NPM,CPRCOR
LOGICAL MIDCYC
INTEGER*2 CYCNUM,CYCRNG,CYCX S,CYCRMX
COMMON/RCDAT/DYDw(3,15),DYP(3,15),GWHXS(3,15),CYCX S(15),
$CYCRMX(15),CYCNUM(18,15),CYCRNG(2,270),ICNO(15),GWHOLD(15),MWD(15)
$,TSY(18,15),TEY(18,15),INSTAT(15),MMIN(15),MMAX(15),MIDMCYC(15)
$,DYHOLD(15),TOY(18,15)
COMMON/PDPERM/S(100,15),ALPHA(100,15),BETAP(1CC,15),FINVAR(100)
INTEGER*2 S
DIMENSION IDNUM(15),NAME(15),INDEX(15)
LOGICAL*1 AL(26)/'A','B','C','D','E','F','G','H','I','J','K','L',
$M','N','O','P','Q','R','S','T','U','V','W','X','Y','Z'/.NPM1
REAL*8 DASHES/'---------'/
5 READ(SIOT,901,END=9) SGTITL
WRITE(WT,902) SGTITL
IF(SGTITL(1).NE.CASHES) GO TO 5
READ(SIOT,903,END=9) NPM1,IDSTG1,SGTITL
WRITE(WT,904) NPM1,IDSTG1,SGTITL
IF((NPM.AND..NCT.NPM1).OR.(.NOT.NPM.AND.NPM1).OR.
$(ICSTRG.NE.IDSTG1)) CALL OPERR(5/"RDSTRG",3)
REAC(SIOT,905,END=9) NCRS,(IDNUM(I),NAME(I),MWMIN(I),
$WMAX(I),INDEX(I),I=1,NCRS)
WRITE(WT,906) NCRS,(I,AL(I),IDNUM(I),NAME(I),MWMIN(I),
$WMAX(I),INDEX(I),I=1,NCRS)
REAC(SIOT,907,END=9) NPERIN
WRITE(WT,970) (I,I=1,9)
CALL ERASE(CYCNM,*MXRCYC*NCRS/2,CYCRNG,*MXRCYC*NCRS)
CTC=0
MXRCMX=0
DO 30 NR=1,NCRS
IF (ICNO(NR).NE.IDNUM(NR)) CALL OPERR('RDSTRG',3)
MXD(NR)=MMAX(NR)-MWMN(NR)
REAC(SIOT,908,END=9) (S(I,NR),I=1,NPERIN)
WRITE(WT,909) NR,IDNC(NR),(S(I,NR),I=1,NPERIN)
MICYC(NR)=.FALSE.
IF(INSTAT(NR)+S(1,NR).EQ.4) MIDCYC(NR)=.TRUE.
J=1
K=0
INIFLG=3
CTOT=CTOT+1
CYCNUM1,NR)=CTOT
CYCRNG1,CTOT)=1
DO 20 I=1,NPERS
IF(K.EQ.2.OR.S(I,NR).AE.2) GO TO 10
INIFLG=INIFLG-1
IF(INIFLG.EQ.2) GO TO 10
J=J+1
CTOT=CTOT+1
CYCNUM(J,NR)=CTOT
CYCRNG(J,CTOT)=I
10 CYCRNG2,CTOT)=I
20 K=S(I,NR)
MXRCMX=MAXO(MXRCMX,J)
30 CYCRNX(NR)=J
ACYC=CTOT
WRITE(WT,910) (I,I=1,NCRS)
DO 40 IC = 1, MXRCMX
40 WRITE(WT,911) IC, (CYCNUM(IC, IR), IR = 1, NRCRS)
WRITE(WT,912) (CYCRMX(IR), IR = 1, NRCRS)
WRITE(WT,913) (IC, CYCRNG(1, IC), CYCRNG(2, IC), IC = 1, NCYCT)
GO TO 50
9 CALL OPERR('RDSTRG',12)
50 RETURN
931 FORMAT(1CA8)
902 FORMAT('RDSTRG READ : ', 'H', 'A8', 'H')
903 FORMAT(L3,17,1O7)
904 FORMAT('Z', 'X', 'NPM+IDSTRG =', 'L2', 'I7', '5X,' $'STRATEGY TITLE : ', 'H', 'A8', 'H')
905 FORMAT(I5/(I5,1X,A4,215,11J))
906 FORMAT('DATA FOR THE ', 'I3', ' REACTORS :/' NR AL IDNO NAME MMM $IN MMM MAX INDEX IN SYSINT'/ (I5,4X,A1,15,A5,15,16,11C))
SC7 FORMAT(21X(14)
908 FORMAT(8011)
909 FORMAT(I5,16,4X,10J1/(15X,10J1))
910 FORMAT('0 CYCNUM(RC,NR) :/' ORCYCLE',T19,'NR REACTOR INDEX'/ $' INDEX',30I4/(9X,30I4))
911 FORMAT('C', 'I4', '3X', '3J14/(10X,30I4))
912 FORMAT('OCYCRMX', '30I4/(10X,30I4))
913 FORMAT('OCYCRNG AS (CYCNUM,FRSPRD,LSTPRD) :'/ $' (1X,10('I', 'I3,214,'')))'
970 FORMAT('/',T20, 'MAINTENANCE STRATEGY BY PERIOD AND INDEX', $' (Q=NON-EXISTENT; 1=DWN; 2=ON-LINE')T/115,1',9I6,'PERIOD'/ $15X,9I10,9X,0'/ NR IDNO',4X,10('1234567890')/) END
SUBROUTINE RDPER
C READS PERIOD INFO OUTPUT BY SYSINT
C SYSOPT VERSION 12-16-72
C IDUM'S USED TO MAKE NAMELIST OUTPUT MORE READABLE
IMPLICIT INTEGER(CG)
REAL*R8 RDFACT,SGTTITL
CCMMCN/OPTLIM/RDFACT,SGTTITL(10),ELAME(40,18),PVRATE,YBASE,YSTART,
$IAUX,IAUXM,NRCRS,NCYCT,NPERS,NPERSP,NPERIN,ITER,MXESX2,MXRCYCX,
$PXNPERMXRCRSMXNJDS,MXARCS,SIOTNPIN,NPCTRDWTPARCALPARCON,
$PARCOP,PCONVG,NPM,IDXSTRG,JFWRWD,JBKWRDNMESH,MSGHE15,MXITER
$,GESFRS,ECUPLM18,CORDTL,OPRCORREJLVLPCEDEA,TH$CONJFRPBK
INTEGER SIOTRCWTPAPCALPARCON,PARCOP
LOGICAL NPMOPRCOR

CCMCM/PDTMP/NPMFAL(100),NTBSLD(100),OPHRS(100,15),LVLMN(100),
$LVLMX(100),PDELIM(20,100),PDTITL(20,100),DMW(100),DTH(100),ECS(100
$),R413,100),R8(12,100),YMID(100),YEND(100),PVFACT(100),AVL(100,
$15),EXPWH(100,15),CAVG(100),BASVAR(100),FINTST(100),MAXVAR(100),
$MAXST(100),MIN(10,15),MAX(100,15),BASCFA(100,15)
REAL MAXVAR,MAXTST,CAVG
REAL*8 PVFACT,R8
COMMON/PROB/DMMDT,GWHPER,DAYS,IEMIN,IEMAX,PEMIN,PEMAX,PROB(500)

REAL DM,DT,GWHPER,DAYS,PEMIN,PEMAX,PROB
REAL*8 DM,DT,GWHPER,DAYS,PEMIN,PEMAX,PROB

$NAMELIST /FNLTOT/MWTOT,MWEAK,MWRG,NMSPIN,PLOFL,
$EXPDEM,EXPGEN,XNGEN,IDUM1,XNGEN,EXPIMR,INDUM2,UNSROD,PROD$,
$IDUM3,SKPRD,SNPRD,INDUM4,SUSD$,SNKL,$IDUM5,SKNSUS,SBTOT,
$IDUM6,SKNTOT,SKNTCT,INDUM7,EMRP,TOTALSES
REAL*8 PRD$,SKPRD,SNPRD,SUSD$,SNKSLS,SBTOT,SKNTCT,
$SNTOT,EMRP,TOTALS

DATA $DASH$,DOTS/'----','....'/
REAL*8 CCFMIN(500),CDFMAX(500)

DIMENSION X(20),Y(20)

10 READ(SIOT,901,END=9) X
IF(X(1).EQ.$CASH$) GO TO 100
IF(X(1).NE.$DOTS$) GO TO 10
READ(SIOT,902,END=9) Y,NPER,DM,DT,DC
IF(NPER.GT.NPERS) GT TO 10
IF(.NOT.NPM) GO TO 20
READ(SIOT,903,END=9) LVLMN(NPER),N1,L1,(CDFMIN(N1+I),I=1,L1)
READ(SIOT,904,END=9) NPMFAL(NPER),NTBSC(NPER),(OPHRS(NPER,I),
$I=1,NRCRS)
LPTS=L1
NUMONE=N1
READ(SIOT,905,END=9) LVLMX(NPER),N1,L1,(CDFMAX(N1+I),I=1,L1)
IF(N1.NE.NUMCNE.OR.LPTS.LT.L1.OR.LVLMN(NPER).GE.LVLMX(NPER))
$ CALL OPEPR('RCPERS',1)
20 READ(SIOT,FLNTOT,END=9)
  REAC(SIOT,905,END=9) (AVL(NPER,I),EXPGWH(NPER,I),I=1,NRCRS)
CO 30 I=1,20
PDELIM(I,NPER)=X(I)
30 FDTITL(I,NPER)=Y(I)
  DMW(NPER)=DM
  CTH(NPER)=DT
  ECS(NPER)=DC
  CWHPER=DM*DT*1.D-3
  IEMIN=NUMONE
  IEMAX=NUMONE+L1
  PEMIN=NUMONE*DM
  PEMAX=IEMAX*DM+1.D-3
  LVLMIN=LVLMN(NPER)
  LVLMAX=LVLMX(NPER)
CO 40 I=1,NUMCNE
  CDFMIN(I)=1.0DC
40 CDFMAX(I)=1.0DO
  R4( 1,NPER)=NPER
  R4( 2,NPER)=MWINST
  R4( 3,NPER)=MWONLN
  R4( 4,NPER)=MWPEAK
  R4( 5,NPER)=MWRMRGN
  R4( 6,NPER)=MWSPIN
  R4( 7,NPER)=PLOFL
  R4( 8,NPER)=EXPDEM
  R4( 9,NPER)=EXPGEN
  R4(10,NPER)=XNKGEN
  R4(11,NPER)=XNNGEN
  R4(12,NPER)=EXPEMR
  R4(13,NPER)=UNSRVD
  R8( 1,NPER)=NPER
  R8( 2,NPER)=PROD$
  R8( 3,NPER)=$NKPRD
R8(4,NPER)=$NNPRD
R8(5,NPER)=SUSC$
R8(6,NPER)=$NKSUS
R8(7,NPER)=$NNSUS
R8(8,NPER)=$SBTOT
R8(9,NPER)=$NKTOT
R8(10,NPER)=$NNTOT
R8(11,NPER)=$EMRP$
R8(12,NPER)=TOTAL$
CALL PDCALC(NPER,CCFMIN,CCDFMAX)
GO TO 10
100 READ(SIOT,906,END=50)
  CALL OPERP(‘ROPERS’,12)
  RETURN
901 FORMAT(20A4)
902 FORMAT(20A4/10,3F10.4)
903 FORMAT(3X,17,2I5,6F10.9/(8F10.9))
904 FORMAT(2I5,(7F10.4))
905 FORMAT(78X,F8.4,18X,F16.5)
906 FORMAT(/)
END
SUBROUTINE PDCALC(NPER,CCFMIN,CCDFMAX)
PERFORMS VARIOUS PRE-CALCS FOR EACH PERIOD
C SYMS OPT VERSION 12-16-72
IMPLICIT INTEGER(4)
REAL*8 RFACT,GSTTL
COMMON/OPTLIM/RFACT,GSTTL(10),ELAME(40,18),PVRATE,YBASE,YSTART,
$IAUX,IAUXM,NCRS,NCYCT,NPERS,NPERSP,NPERIN,ITER,MXESX2,MXRCYC,
$MXNPER,MXRCS,MXNODS,MXARCS,SIOT,NPIN,NPT,RD,WT,PARCAL,PARCON,
$PARCCP,PCONVG,NPM,IDSTRG,JFRWRD,JBMWRD,NMESH,MESHER(15),MXITER
$GESFRS,ECUPLM(18),CORCTL,CPRCOR(6),REJLVL,PCDELA,TH$CON,JFRPBK
INTEGER SIOT,RD,WT,PARCAL,PARCON,PARCCP
LOGICAL NPM,OPRCOR
LOGICAL MIDCYC
INTEGER CYCNUM,CYCRAG,CYCXS,CYCRMX
COMMON/RCRDAT/DYDWN(3,15),DYUP(3,15),GWHXS(3,15),CYCXS(15),
$CYCRMX(15), CYCNUM(18,15), CYCRNG(2,270), ICNO(15), GWHOLD(15), MWD(15)$
$TSY(18,15), TEY(18,15), INSTAT(15), MMWIN(15), MMWAX(15), MICCYC(15)$
$DYHOLD(15), TOY(18,15)$
$COMMON/PDPERM/S(100,15), ALPHA(100,15), BETAP(100,15), FINVAR(100)$
$REAL MAXVAR, MAXTST, CAVG$
\[ SP\text{MX}=\text{SPMX}+\text{P} \times \text{MX} \]
\[ SP\text{MN}=\text{SPMN}+\text{P} \times \text{MN} \]
\[ \text{MWCMIN}=\text{MINO} (\text{MWCMIN}, \text{MWD(NR)}) \]
\[ \text{GWHBAS}=\text{OPHRS}(\text{NP}, \text{NR}) \times \text{MW} \times 0.01 \]
\[ \text{BASCFA}(\text{NP}, \text{NR})=100 \times \text{OPHRS}(\text{NP}, \text{NR}) / (\text{DT} \times \text{P}) \]
\[ \text{ALPHA}(\text{NP}, \text{NR})=1000 / (\text{MW}(\text{NR}) \times \text{P} \times \text{DT}) \]
\[ \text{BETAP}(\text{NP}, \text{NR})=\text{GWHBAS} \times \text{ALPHA}(\text{NP}, \text{NR}) \]
\[ \text{CALL} \; \text{SUBPLT}(\text{MN}, \text{P}, \text{CDFMIN}) \]
\[ \text{MAX}(\text{NP}, \text{NR})=\text{GWHBAS} + \text{P} \times \text{GWH}(\text{LVLMIN}, \text{LVLMIN} + \text{MWC}(\text{NR})) \times 0.5 \]
\[ \text{CALL} \; \text{SUBPLT}(\text{MX}, \text{P}, \text{CDFMAX}) \]
\[ \text{MIN}(\text{NP}, \text{NR})=\text{GWHBAS} + \text{P} \times \text{GWH}(\text{LVLMAX} - \text{MWD(NR)}, \text{LVLMAX}) \times 0.5 \]

GO TO 30

20 \text{MIN}(\text{NP}, \text{NR})=0
\text{MAX}(\text{NP}, \text{NR})=0
\text{BASCFA}(\text{NP}, \text{NR})=-100.

30 \text{CONTINUE}

\text{IF(MWDTOT} \neq \text{LVLMAX-LVLMIN) CALL OPEPR('PDCALC', 2)}

\text{CALCULATE CDFLPR AND CAVG}

\text{IF(MWDTOT} \leq 0) \text{GO TO 36}

\text{P} \times \text{MX}=\text{SPMX} / \text{IMX}
\text{F} \times \text{MN}=\text{SPMN} / \text{IMN}
\text{MNBAR}=\text{FLAT}(\text{IMN}) / \text{NRON} + 0.5
\text{MNBAR}=\text{FLOAT}(\text{IMN}) / \text{NRON} + 0.5

\text{CALL} \; \text{SUBPLT}(\text{MNBAR}, \text{P} \times \text{MN}, \text{CDFMIN})

\text{DO 32 I=1, IEMAX}
\text{CDFMIN(I)}=\text{PROB}(I)

\text{CALL} \; \text{SUBPLT}(\text{MNBAR}, \text{P} \times \text{MN}, \text{CDFMAX})

\text{DO 34 I=1, IEMAX}
\text{CDFMAX(I)}=\text{PROB}(I)

36 \text{ILO}=(\text{LVLMIN} -.01) / \text{DM}
\text{IF}((\text{ILO} \leq \text{IEMIN}) \text{ ILO}=	ext{IEMIN} + 1
\text{IHI}=(\text{LVLMAX} + .01) / \text{DM} + 1
\text{TEMP}=1 / \text{MWDTOT}

\text{DO 38 I=ILO, IHI}
\text{F}=(1 \times \text{DM} - \text{LVLMIN}) \times \text{TEMP}

38 \text{CDFLPR(I)}=\text{CDFMIN(I)} + \text{F} \times (\text{CDFMAX(I)} - \text{CDFMIN(I)})
CAVE = G(WH(LVL_MIN, LVL_MAX) / (MWDTOT * DT * 0.001)
CAVG(NP) = CAVE
CMAX = PROBX(DFLOAT(LVL_MIN))
CMIN = PROBX(DFLOAT(LVL_MAX))
IF(NRON.LE.0.OR.CMIN.CE.1.D0) GO TO 60
C
!EASVAR
VAR = 0.0
LVL = LVL_MIN
KBLKS = (MWDTOT - 1) / MWDMIN + 1
TEMP = 1000. / (MWDMIN * CT)
D 40 K = 1, KBLKS
CI = GWH(LVL, LVL + MWDMIN) * TEMP
LVL = LVL + MWDMIN
40 VAR = VAR + (CI - CAVE)**2
BASVAR(NP) = VAR / KBLKS
C
!MAXVAR
F = (CAVE - CMIN) / (CMAX - CMIN)
MAXVAR(NP) = F*(CMAX - CAVE)**2 + (1. - F)*(CAVE - CMIN)**2
MAXTST(NP) = MAXVAR(NP) / BASVAR(NP)
C
!FINVAR
C 50 I = IEMIN, IEMAX
C
D 50 CDFLPR(I) = CDFLPR(I)**2
FINVAR(NP) = G(WH(LVL_MIN, LVL_MAX) / (MWDTOT * DT * 0.001) - CAVE)**2
FINST(NP) = FINVAR(NP) / BASVAR(NP)
C
50 TO 70
60 MAXVAR(NP) = 0.0
MAXTST(NP) = 0.0
FINVAR(NP) = 0.0
FINST(NP) = 0.0
BASVAR(NP) = 1. E15
C
70 RETURN

END

SUBROUTINE SUBPLT(MW, P, CDF)
C
!SUBTRACTS PLANT OF MW MEGAWATTS AND P FRACTIONAL AVAILABILITY
FROM PROB, THE EQUIVALENT LOAD CDF
C
!SYSOPT VERSION 03-06-72

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C NOTE: MW MUST BE LESS THAN PEMIN
IMPLICIT REAL*8 (A-H,C-1)
COMMON/PROB/DM,DT,GWHPER,DAYS,IEMIN,IEMAX,PEMIN,PEMAX,PROB(500)
$LVMIN, LVMAX
REAL*8 ZERO/0.000/, CNE/1.000/, TWO/2.000/, HALF/0.500/, TEN/1.00/
$TENTH/1.D-1/, HUNDRED/1.D2/, CENTI/1.D-2/, THOUS/1.D3/, MILLI/1.D-3/
CIMENSION CDF(1)
DATA EPS,TRACE/1.0-3,1.0-10/
CO 10 J=1,IEMAX
10 PROB(J)=CDF(J)
    IF(MW.LE.0.) RETURN
    IF(MW.GE.PEMIN) CALL CERP('SUBPLT',2)
    ILow=IEMIN+1
    FB=MW/DM
    INT=FB
    FB=FB-INT
    CVP=ONE/P
    G=CNE-P
    QFB=Q*FB
    GAMMA=ONE/(CNE-QFB)
    IF(INT.GT.0.) GO TO 60
    C LOOP TO UNCONVOLVE PLANT IF MW.LT.DM
    CO 20 J=ILow,IEMAX
    20 PROB(J)=GAMMA*(PROB(J)-QFB*PROB(J-1))
    C FINE NEW PEMAX AND IEMAX
    30 J=IEMAX
    40 IF(PROB(J).GT.TRACE) GO TO 50
    FRCB(J)=ZERO
    J=J-1
    GO TO 40
    50 IF(IEMAX.EQ.J) RETURN
    IEMAX=J+1
    PEMAX=IEMAX*DM+EPS
    RETURN
    C LOOP TO UNCONVOLVE PLANT IF MW.GE.DM
    60 GO 70 J=ILow,IEMAX
JINT=J-INT
70 PROB(J)=CVP*(PROB(J)-C*(PROB(JINT)+FB*(PROB(JINT-1)-PROB(JINT))))
GO TO 30
END

FUNCTION GWHNRG(XLOWER,XUPPER)
C CALCULATES GWH OF ENERGY UNDER PORTION OF PROCB, THE CDF OF
C EQUIVALENT LOAD, BY INTEGRATING FROM XLOWER TO XUPPER ASSUMING
C LINEAR INTERPOLATION BETWEEN ARRAY POINTS
C SYSOPT VERSION 03-06-72
IMPLICIT REAL*8 (A-H,O-)
COMMON/PROB/DM,DT,GWHPER,DAYS,IEMIN,IEMAX,PEMIN,PEMAX,PROB(500)
$DLV.MIN,DLV.MAX
REAL*8 ZERO/0.0D0/,ONE/1.0D0/,TWO/2.0D0/,HALF/0.5D0/,TEN/1.01/,
$TENTH/1.0D-1/,HUNDRED/1.0D-2/,THOUS/1.0D-3/,MILLI/1.0D-3/
XLC=XLOWER
XUP=XUPPER
GWHNRG=ZERO
SUM=ZERO
IF(XLOWER.GE.XUPPER) RETURN
IBELC=XLOWER/DM
ILAST=XUPPER/DM
IF(IBELC.LE.0.OR.ILAST.GE.IEMAX) GO TO 5C
IF(IEBELC.EQ.0.OR.ILAST.GE.IEMAX) GO TO 5C
5 IFRST=IBELC+1
IABOV=ILAST+1
IFRSTP=IFRST+1
ILASTM=ILAST-1
ICASE=IABOV-IBELC
RLC=IFRST-XLOWER/DM
RUP=XUPPER/DM-ILAST
FLC=PROB(IFRST)+PROB(IBELC)-(PROB(IFRST)-PROB(IBELC))*RLO
PUP=PROB(IABOV)+PROB(ILAST)-PROB(IABOV)*(ONE-RUP)
GO TO (10,20,30,40),ICASE
30 SUM=SUM+HALF*(PROB(IFRST)+PROB(ILAST))
20  SUM = SUM + HALFW*RLC*(PLO + PROB(IFST)) + RUP*(PUP + PROB(ILAST))
15  GWLNRC = SUM*GWHPER
       RETURN
10  SUM = SUM + (XUP - XLO)*(PLC + PUP)*HALF/DM
       GO TO 15
C
SPECIAL CASES INVOLVING ONE OR BOTH END POINTS
50  IF(XLP .LE. ZERO .OR. XLC .GE. PEMAX) RETURN
   IF(XLO .LT. ZERO)  XLC = ZERO
   IF(XUP .GT. PEMAX)  XUP = PEMAX
   IBELC = XLO/DM
   ILAST = XUP/DM
   JCASE = 1
   IF(ILAST .GT. 0)  JCASE = JCASE + 1
   IF(ILAST .EQ. IEMAX)  JCASE = JCASE + 1
   IF(IBELC .GT. 0)  JCASE = JCASE + 1
   IF(IBELC .EQ. IEMAX)  JCASE = JCASE + 1
   GO TO (101, 102, 102, 104, 105), JCASE
101  GWLNRC = (XUP - XLO)*GWHPER/DM
       RETURN
102  SUM = ONE - XLO/DM
       XLO = DM
       IBELC = 1
   IF(JCASE .EQ. 2) GO TO 5
104  XO = IEMAX*DM
   FUP = PROB(IEMAX)*ONE - (XUP - XO)/(PEMAX - XO)
   SUM = SUM + (XUP - XO)*HALF*(FUP + PROB(IEMAX))/CM
   XUP = XO
   ILAST = IEMAX - 1
   GO TO 5
105  XO = IEMAX*DM
   FUP = PROB(IEMAX)*ONE - (XUP - XO)/(PEMAX - XO)
   FLO = PROB(IEMAX)*ONE - (XLC - XO)/(PEMAX - XO)
   GWLNRC = (XUP - XLC)*(FLC + FUP)*HALF*GWHPER/DM
       RETURN
END
FUNCTION PROBX(X)
C EVALUATES PROB AT A PARTICULAR VALUE OF X MW
C SYSOPT VERSION 03-06-72
IMPLICIT REAL*8 (A-H,0-$)
CCMMCN/PROB/DM,DT,GWHPER,DAYS,IEMIN,IEMAX,PEMIN,PEMAX,PROB(500)
$LVLMIN,LVLMAX
DATA ZERO,ONE/0.000,1.000/
PRCBX=ONE
IF(X.LE.PEMIN) RETURN
PRCBX=ZERO
IF(X.GE.PEMAX) RETURN
FB=X/DM
ILO=FB
FB=FB-ILO
IF(ILO.GE.IEMAX) GO TO 10
PROBX=PROB(ILO)+FB*(PROB(ILO+1I)-PROB(ILO))
RETURN
10 PRCBX=PRCB(IEMAX)*(PEPAX-X)/(PEMAX-IEMAX*DM)
RETURN
END
SUBROUTINE ASMTYS
ASSEMBLES TSY'S AND TEY'S
C SYSCPT VERSION 12-16-72
IMPLICIT INTEGER(C,G)
REAL*8 RDFACT,SGTTL
CCMMCN/OPTLIM/RDFACT,SGTTL(10),ELAME(40,18),PVRATE,YBASE,YSTART,
$IAUX,IAUXM,NRCRS,NCYCT,NPERS,NPERSP,NPERIN,ITER,MXESX2,MXRCYC,
$MNPC,RXCRS,MXNDCS,MXARCS,SIOT,NPCT,RT,WT,PARCAL,PARCON,
$PARCOP,PCONVG,NPM,IDSTRG,JFRRWD,GBKURD,NMESH,MESH(15),MXITER
$GESFRS,ECUPLM(18),CORDTL,OPRCOR(6),REJNLVL,PCDELA,TH$CONJFRPBK
INTEGER SIOT,RT,WT,PARCAL,PARCON,PARCOP
LOGICAL NPM,OPRCOR
LOGICAL MIDCYC
INTEGER*2 CYCNUM,CYCRANG,CYCXS,CYCRMX
COMMON/RCRDAT/CYOWN(3,15),DYUP(3,15),GWHXS(3,15),CYCXS(15),
$CYCRMX(15),CYCNUM(18,15),CYCRANG(2,270),INOD(15),GWHOLD(15),MW(15)
$TSY(18,15),TEY(18,15),INSTAT(15),MVMIN(15),MVMAX(15),MIDCYC(15)
$,DYHCLD(15),TOY(18,15)
COMMON/PDPERM/S(100,15),ALPHA(100,15),BETAP(100,15),FINVAR(100)
INTEGER*2 S
CCMCN/PDTEMP/NPMFAL(100),NTBESLD(100),OPHRS(100,15),LVLMN(100),
*LVLMX(100),PDELM(20,100),PDTITL(20,100),DMW(100),DTH(100),ECS(100)
$,R4(13,100),R8(12,100),YMID(100),YEND(100),PVFACT(100),AVL(100,
*15),EXPGWH(100,15),CAVG(100),BASVAR(100),FINTST(100),MAXVAR(100),
*MAXST(100),MIN(100,15),MAX(100,15),BASCFA(100,15)
REAL MAXVAR,MAXST,CAVG
REAL*8 PVFACT,RE
LOGICAL WASUP,DWNUW
INTEGER RC
PVP(Y)=PVPERS(Y,YBASE)
TEMP=0.5/8760.
YEND(1)=YSTART+DTH(1)/8760.
YMID(1)=(YSTART+YEND(1))/0.5
PVFACT(1)=PVP(YMID(1))
CO 10 NP=2,NPERS
X=TEMP*DTH(NP)
YMID(NP)=YEND(NP-1)+X
YEND(NP)=YMID(NP)+X
1) PVFACT(NP)=PVP(YMID(NP))
CO 50 NR=1,NRCLS
IC=1
TOY(IC,NR)=0.0
IF(MIDCYC(NR)) IC=0
CLIM=CYCRMX(NR)
CO 30 RC=1,CLIM
CYC=CYCNUM(RC,NR)
NPL=CYCRNG(1,CYC)
NPF=CYCRNG(2,CYC)
IC=IC+1
TOY(IC,NR)=0.0
WASUP=.FALSE.
DO 20 NP=NPF,NPL
TOY(IC,NR)=TOY(IC,NR)+OPHRS(NP,NR)/8760.
CWNCW = S(NP, NR) . NE. 2
IF (WAASUP . AND. DWNOW) GO TO 30
IF (WAASUP . AND. NOT. CWNCW) GO TO 20
IF (.NJ.T. WAASUP . AND. DWNCW) GO TO 20
WAASUP = .TRUE.
TSY(IC, NR) = YEND(NP - 1)
IF (NP . EQ. 1) TSY(IC, NR) = YSTART
20 TEY(IC, NR) = YEND(NP)
3) CONTINUE
   TEY(IC, NR) = TEY(IC, NR) + DYHOLD(NR)
   TOY(IC, NR) = TOY(IC, NR) + DYHOLD(NR) * AVL(NPERS, NR) * 0.01
IF (MIDCYC(NR)) GO TO 35
   TEY(I, NR) = TSY(2, NR)
TSY(1, NR) = TSY(2, NR) - 1.E-4
35 N CYCXS = CYCXS(NR)
IF (NCYCXS . LT. 1) GO TO 50
DO 40 I = 1, N CYCXS
   IC = IC + 1
TSY(IC, NR) = TEY(IC - 1, NR) + DYDWN(I, NR)
   TOY(IC, NR) = DYUP(I, NR) * AVL(NPERS, NR) * 0.01
40 TEY(IC, NR) = TSY(IC, NR) + DYUP(I, NR)
50 CONTINUE
RETURN
END

SUBROUTINE WTPERS
WRTES INFO. FOR THE VARIOUS PERIODS
C
C SYSOPT VERSION 12-16-72
C
IMPLICIT INTEGER(C, G)
REAL*8 RFACT, GTPITL
COMMON/OPTLIM/RDFACT, GTPITL(10), ELAME(40, 18), PVRATE, YBASE, YSTART,
$IAUX, IAUXP, NRCRS, NNCYT, NPERSONS, NPERSP, NPERIN, ITER, MXESX2, MXRCYC,
$*MXPER, MXCRS, MXNODS, MXARC, SIOT, NPIN, NPCRT, RD, WT, PARCAL, PARCON,
*PARCCP, PCONVG, NPM, IDSTRG, JFRWRD, JBKWRD, NMESH, MESH(15), MXITER
$GEFRS, ECUPLM(18), CCRRTL, CPARCC(6), REJLVL, PCDELTA, TH$CON, JFRPBK
INTEGER SIOT, RD, WT, PARCAL, PARCON, PARCCP
LOGICAL NPM, OPRCPR
LOGICAL MIDCYC
INTEGER*2 CYCNUM,CYCRNG,CYCXS,CYCRMX
COMMON/RCRDAT/DYDWN(3,15),DYUP(3,15),GWHXS(3,15),CYCXS(15),
$CYCRMX(15),CYCNUM(18,15),CYCRNG(2,270),IDNO(15),GWHOLD(15),MWD(15)
$,TSY(18,15),TEY(18,15),INSTAT(15),MWMIN(15),MWMAX(15),MIDCYC(15)
$,DYFOLD(15),TOY(18,15)
COMMON/PDPERM/S(110,15),ALPHA(100,15),BETAP(100,15),FINVAR(100)
INTEGER*2 S
COMMON/PDTMP/NPMFAL(100),NTBSLD(100),OPFRS(100,15),LVLMN(100),
$LVLMX(100),PDELIM(20,100),PDTITL(20,100),CMW(100),ETH(100),ECS(100)
$,R4(13,100),R8(12,100),YMD(100),YEND(100),PVFACT(100),AVL(100,
$15),EXPGWH(100,15),CAVG(100),BASVAR(100),FINST(100),MAXVAR(100),
$MAXST(100),MIN(100,15),MAX(100,15),BASCFA(100,15)
REAL MAXVAR,MAXTST,CAVG
COMMON/FINALS/S4,SA4,SP4,SL4,SP8
REAL*8 S4(13),SA4(13),SP4(13),SL4(13),SP8(13)
REAL*8 S8(13),SA8(13),SL8(13),SPV,PV,PVFCT,R8
CALL ERASE(S4,26,SA4,26,SP4,26,SL4,26,S8,26,SA8,26,SP8,26,SL8,26)
SPV=0.0D0
DO 20 I=1,NPERS
IF(R4(I,1).NE.1) CALL OPPER('WTPERS',12)
PV=PVFACT(I)
SPV=SPV+PV
CO 10 J=2,12
S4(J)=S4(J)+R4(J,1)
S8(J)=S8(J)+R8(J,1)
SP4(J)=SP4(J)+PV*R4(J,1)
10 SP8(J)=SP8(J)+PV*R8(J,1)
S4(13)=S4(13)+R4(13,1)
SP4(13)=SP4(13)+PV*R4(13,1)
20 SP8(13)=SP8(13)+PV*R8(13,1)
CO 30 J=2,12
SA4(J)=SA4(J)/NPERS
SL4(J)=SL4(J)/SPV
SA8(J)=SA8(J)/NPERS
30 SLE(J) = SP8(J)/SPV
SA4(13) = S4(13)/NPERS
SL4(13) = SP4(13)/SPV
WRITE(WT,901) (I,(PDELM(J,I),J=1,20),I=1,10)
WRITE(WT,902) (I,(PDITL(J,I),J=1,20),I=1,10)
WRITE(WT,903) (I,DMW(I),ECST(I),DTH(I),YMID(I),Y ENC(I),PVFACT(I),
$NPMFAL(I),NTBSLD(I),LVLMN(I),LVLMX(I),I=1,10)
WRITE(WT,915) SPV,(I,I=1,NMRCYC)
DO 35 NR=1,NRCS
CLIM=CYCRMX(NR)+CYCXS(NR)
IF(.NOT.IVDCYC(NR)) CLIM=CLIM+1
IF(CLIM.GT.MXRCYC) CALL OPERR('WTPERS',6)
WRITE(WT,916) NR,TSY(I,NR),I=1,CLIM
WRITE(WT,919) (TOY(I,NR),I=1,CLIM)
WRITE(WT,911)
WRITE(WT,904) (I,I=1,NRCS)
WRITE(WT,905) (AL(I),I=1,NRCS)
DO 40 I=1,NPERS
WRITE(WT,906) I,(AVL(I,NR),NR=1,NRCS)
WRITE(WT,912)
WRITE(WT,904) (I,I=1,NRCS)
WRITE(WT,905) (AL(I),I=1,NRCS)
DO 50 I=1,NPERS
WRITE(WT,906) I,(OPHRS(I,NR),NR=1,NRCS)
WRITE(WT,918)
WRITE(WT,904) (I,I=1,NRCS)
WRITE(WT,905) (AL(I),I=1,NRCS)
DO 55 I=1,NPERS
WRITE(WT,906) I,(BASCFA(I,NR),NR=1,NRCS)
WRITE(WT,913)
WRITE(WT,904) (I,I=1,NRCS)
WRITE(WT,905) (AL(I),I=1,NRCS)
DO 60 I=1,NPERS
WRITE(WT,906) I,(EXPGWH(I,NR),NR=1,NRCS)
WRITE(WT,907) (R4(I,J),I=1,13),J=1,10
35 WRITE(WT,917) (TEY(I,NR),I=1,CLIM)
WRITE(WT,911)
WRITE(WT,904) (I,I=1,NRCS)
WRITE(WT,905) (AL(I),I=1,NRCS)
DO 40 I=1,NPERS
WRITE(WT,906) I,(AVL(I,NR),NR=1,NRCS)
WRITE(WT,912)
WRITE(WT,904) (I,I=1,NRCS)
WRITE(WT,905) (AL(I),I=1,NRCS)
DO 50 I=1,NPERS
WRITE(WT,906) I,(OPHRS(I,NR),NR=1,NRCS)
WRITE(WT,918)
WRITE(WT,904) (I,I=1,NRCS)
WRITE(WT,905) (AL(I),I=1,NRCS)
DO 55 I=1,NPERS
WRITE(WT,906) I,(BASCFA(I,NR),NR=1,NRCS)
WRITE(WT,913)
WRITE(WT,904) (I,I=1,NRCS)
WRITE(WT,905) (AL(I),I=1,NRCS)
DO 60 I=1,NPERS
WRITE(WT,906) I,(EXPGWH(I,NR),NR=1,NRCS)
WRITE(WT,907) (R4(I,J),I=1,13),J=1,10
SUBROUTINE SETUPN

SETS UP COSTS AND LIMITS OF REMAINING ARCS IN THE NETWORK

IMPLICIT INTEGER(C,G)

REAL*8 RCFACT,SGTITL

COMMON/OPTL IM/RCFACT,SGTITL(10),ELAME(40,18),PVRATE,YBASE,YSTART,
* 1AUX,I Aux,NRCRS,NPERS,NPERSP,NPERIN,ITER,MXESX2,MXRCYC,
*MXNPER,MXCRS,MXNODS,MXARC,SIOT,NPIN,NPCT,RC,WT,PARCAL,PARCON,
*PARCOP,PCONV,PNM,IDSTRG,JFRWD,TBKWDR,WME,PWME,PWME,HME(15),MXITER
*S,GESFRS,ECUPLM(18),CCRDTL,CPRCOR(6),REJLVL,PCDELA,TH$CON,JFRPBK

INTEGER SIOT,RC,WT,PARCAL,PARCON,PARCOP

LOGICAL APM,OPRCOR

LOGICAL MIDCYC

INTEGER CYCNUM,CYCRNG,CYCRMX

COMMON/RCDAT/DYDWN(3,15),DYUP(3,15),GWHXS(3,15),CYCXS(15),
*S,CYCRNG(15),CYCNUM(18,15),CYCRNG(2,270),ICNO(15),GWHOLD(15),MWD(15)
*S,TSY(18,15),TEY(18,15),INSTAT(15),MWM(15),MWMIN(15),MWMAX(15),MIDCYC(15)
*S,DYHO(15),TOY(18,15)

COMMON/PDPERM/S(100,15),ALPHA(100,15),BETAP(100,15),FINVAR(100)

INTEGER S

COMMON/KC/KC(1)/KU/KU(1)/KL/KL(1)

COMMON/PCTEMP/NPMFAI(100),NTBSDL(100),OPHRS(100,15),LVLMN(100),
*S,LVLMX(100),PDELIM(20,100),PDTITL(20,100),DMW(100),CEH(100),ECS(100)
*S,R4(13,100),R4(12,100),VMID(100),YEND(100),PFACT(100),AVL(100,
*S,15),EXPGW(100,15),CAVG(100),BASVAR(100),FINST(100),MAXVAR(100),
$\text{MAXTST}(100), \text{MIN}(100, 15), \text{MAX}(100, 15), \text{BASCFA}(100, 15)$

REAL MAXVAR, MAXTST, CAVG

REAL*8 PVFACT, R8

INTEGER RC

DATA LARGE/2000000000/

REAL*8 SUMD

LOGICAL GESEQ1, GESEQ2, GESGT2

CALL ERASE(KC, MXARCS, KU, MXARCS, KL, MXARCS)

SUMD = 0.0D0

KSUM = 0

L = LOC(6, 0, 0, 1) - 1

DO 6 NP = 1, NPERS

LSUM = 0

DO 4 NR = 1, NRCRS

LSUM = LSUM + MAX(NP, NR)

4

LSUM = LSUM + MAX(NP, NR)

5

TYPE 6

K = L + NP

KU(N) = R4(10, NP) + 0.5

IF(KU(N) .GT. LSUM) KU(N) = LSUM

KL(N) = KU(N)

KSUM = KSUM + KU(N)

SUMD = SUMD + R4(10, NP)

RDFACT = SUMD / KSUM

WRITE(WT, 900) RDFACT

CDEL = 10

IF(GESFRS .EQ. 4) GDEL = 0

GESEQ1 = GESFRS .EQ. 1

GESEQ2 = GESFRS .EQ. 2

GESGT2 = GESFRS .GT. 2

DO 30 NR = 1, NRCRS

L = LOC(4, NR, 0, NPERS)

C

TYPE 4

WRITE(WT, 900) RDFACT

KU(L) = GWHOLD(NR)

KL(L) = KU(L)

L = LOC(4, NR, 1, 1) - 1

CLIM = CYCRMX(NR)
CO 30 RC=1, CLIM
C=CYCNUM(RC, NR)
ILO=CYCRNG(1, C)
IHI=CYCRNG(2, C)
CMIN=0
CINC=0
CMAX=0
CO 10 J= ILO, IHI
C TYPE 4 PERIODS
N=L+J
KL(N)=MIN(J, NR)
KU(N)=MAX(J, NR)
CMID=CMID+EXPGWH(J, NR)+0.5
CMIN=CMIN+KL(N)
CMAX=CMAX+KU(N)
GO TO 20
IF (IHI .NE. NPERS) GO TO 20
CMIN=CMIN+KL(L+NPERSP)
CMID=CMID+KU(L+NPERSP)
CMAX=CMAX+KU(L+NPERSP)
C TYPE 1
20 KL(C)=CMIN
KU(C)=CMAX
C TYPE 2
IF (GESGT 2) GO TO 26
IF (GESEQ1) GO TO 25
IF (GESEQ2) KC(C+NCYCT)=ELAME(NR, RC)
KL(C+NCYCT)=CMIN/10*10
KU(C+NCYCT)=(9+CMAX)/10*10
GO TO 30
25 KL(C+NCYCT)=CMID-5
KU(C+NCYCT)=CMID+5
GO TO 30
26 KU(C+NCYCT)=ELAME(NR, RC)+GDEL
KL(C+NCYCT)=ELAME(NR, RC)-GDEL
LAUX=LOC(3, NR, RC, 0)
KC(LAUX)=10000
KU(LAUX)=100000
LAUX=LAUX+1
KC(LAUX)=-10000
KL(LAUX)=-10000

30 CONTINUE
L=LOC(5,0,0,0)

C
TYPE 5
KU(L)=LARGE
KU(L+1)=LARGE
KU(L+2)=LARGE
CO 60 NR=1,NRCRS
CO 60 NP=1,NPER
L=LOC(4,NR,0,NP)
MC\n=KL(L)
MD\n=KU(L)
IF(MCX.LE.0) GO TO 60
MAV=(CAVG(NP)+BETAP(NP,NR))/(ALPHA(NP,NR)+0.5
MD\n=(MD\n-MAV)/(JFRWRD-1)+1
MDN=(MAV-MON)/JBKWRD+1
L=LOC(7,NR,0,NP)-1

C
TYPE 7
KU(L+1)=MAV
KL(L+1)=KU(L+1)
CO 40 J=2,JFRWRD
KC(L+J)=(J-1)**4
40 KU(L+J)=MD\n
L=L+JFRWR
\n\nIF(JBKWRD.LE.0) GO TO 60
CO 50 J=1,JBKWRD
KC(L+J)=-J**4
50 KL(L+J)=-MD\n
60 CONTINUE
CALL CNLY$$
RETURN

900 FORMAT('0',T6,F12.8,' = RDFACT, NUCL*GEN*ROUND-OFF CORRECTION FACT
**CR')
END

SUBROUTINE SETLPT
SETS UP INPUT TAPE FOR 0-0-K

C

SYOPT VERSION 12-16-72

IMPLICIT INTEGER(C,G)

REAL*8 RFACT, STITL

COMMON/OPTLIM/RDFACT, STITL(L), ELAME(4,18), PVRATE, YBASE, YSTART,
$IAUX, IAXM, NRCRS, NCYCT, NPER, NPERSP, NPERIN, ITER, MXESX2, MXRCYC,
$MXPER, MXRCS, MXNDS, MXARCS, SITOT, NPCT, RC, WT, PARCAL, PARCON,
$PARCCP, PCONVRG, NPM, IDISTRG, JFRWRD, JBKWRD, NMECH, MESH(15), MXITER
$,GESSRS, ECUPLM(18), CORCTL, OPRCOR(6), REJLVL, PCDELA, TH$CON, JFRPBP

INTEGER SIOT, RD, WT, PARCAL, PARCON, PARCCP

LOGICAL NPM, OPRCOR

LOGICAL MIDCYC

INTEGER*2 CYCNUM, CYCRNG, CYCXS, CYCRMX

COMMON/RCDAT/CYCNUM(3,15), CYCXS(3,15), GWHXS(3,15), CYCXS(15),
$CYCRMX(15), CYCNUM(18,15), CYCRNG(2,270), NCUR(15), GW$OLD(15), MWD(15)
$,TSY(18,15), TEL(18,15), INSTAT(15), MWMIN(15), MMAX(15), MIDCYC(15)
$,DYHOLD(15), TOY(18,15)

COMMON/KC/KK(1)/KU/KU(1)/KL/KL(1)


INTEGER RC

REWIND NPIN

WRITE(NPIN,931) SITL

L=0

C

DO 101 NR=1, NRCRS

CLEM=CYCRMX(NR)

AR=AL(NR)

DO 101 RC=1, CLIM

L=L+1

101 WRITE(NPIN,901) AR, RC, AR, RC, KC(L), KU(L), KL(L)

C

TYPE 2

DO 102 NR=1, NRCRS

CLIM=CYCRMX(NR)
AR=AL(NR)
102 WRITE(NPIN,902) AR,RC,KC(L),KU(L),KL(L)
C TYPE 3
DO 103 NR=1,NRCRS
CLIM=CYCRMX(NR)
AR=AL(NR)
DO 103 RC=1,CLIM
DO 103 I=1,IAUXM
L=L+1
103 WRITE(NPIN,902) AR,RC,KC(L),KU(L),KL(L)
C TYPE 4
DO 104 NR=1,NRCRS
CLIM=CYCRMX(NR)
AR=AL(NR)
DO 104 RC=1,CLIM
CYC=CYCNUM(RC,NR)
ILC=CYCRNG(1,CYC)
IHI=CYCRNG(2,CYC)
DO 104 NP=ILC,IHI
L=L+1
104 WRITE(NPIN,904) AR,RC,AR,NP,KC(L),KU(L),KL(L)
L=L+1
114 WRITE(NPIN,914) AR,CLIM,KC(L),KU(L),KL(L)
C TYPE 5
L=L+1
LP2=L+2
WRITE(NPIN,905) (KC(N),KU(N),KL(N),N=L,LP2)
L=LP2
C TYPE 6
WRITE(NPIN,906) (N,KC(L+N),KU(L+N),KL(L+N),N=1,NPERS)
L=L+NPERS
C TYPE 7
JGTAL=JFRWPD+JBKWRD
DO 107 NP=1,NPERS
DO 107 NR=1,NRCRS
AR=AL(NR)
COMMON/AR(10),KU(L),KL(L)
CC 107 J=1,JTOTAL
L=L+1
107 WRITE(NPIN,907) AR,NP,PKC(L),KU(L),KL(L)
CUMARC=NCYCT*(IAUX+1)+NPER*(JFRWRD+JBKWRD+1)*NRCRS+1+NRCS+3
IF(L.NE.CUMARC) CALL OPERR('SETUPT',4)
WRITE(NPIN,932)
J=2+MXITEP
WRITE(NPIN,933)
END FILE NPIN
REWIND NPIN
RETURN
901 FORMAT(6X,'R',A1,'C',I2,'A', 'R',A1,'C',I2,'T21,3110)
902 FORMAT(6X,'NUKFUL', 'R',A1,'C',I2,'A', T21,3110)
904 FORMAT(6X,'DEMAND', 'DUMMY', T21,3110/
$ 6X,'HLDOVR', 'DUMMY', T21,3110/
$ 6X,'DUMMY', 'NUKFUL', T21,3110)
906 FORMAT(6X,2X,'P',I3,'DEMAND', T21,3110)
907 FORMAT(6X,'R',A1,'P',I3, 'I3', T21,3110)
908 FORMAT(6X,2X,'P',I3,'R',A1,'P',I3, T21,3110)
914 FORMAT(6X,'R',A1,'C',I2,'HLDOVR', T21,3110)
931 FORMAT('READY'/10A7/'ARCS')
932 FORMAT('END'/10A7/'OUTPUT PRINTER'/10A7/'COMPUTE'/10A7/'PAUSE')
933 FORMAT('SAVE'/10A7/'OUTPUT PRINTER'/10A7/'COMPUTE'/10A7/'PAUSE')
END
SUBROUTINE CONVRG(OPTRCH,$LAST)
SUPERVISES CONVERGENCE BETWEEN O-O-K AND IN-CORE MODEL
C SYSOPT VERSION 12-16-72
IMPLICIT INTEGER(C,G)
REAL*8 RFFACT,SGTITL
COMMON/OPTLM/RFFACT,SGTITL(10),ELAME(40,18),PWRATE,YBASE,YSTART,
$IAUX,IAUXM,NRCRS,NCYCT,NPERS,NPERSP,NPERIN,ITER,MXESX2,MXRCYC,
$MXNPER,MXCRS,MXNODS,MXARCS,SIOT,NPIN,NPCT,RC,WT,PARCAL,PARCCN,
$PARCCP,PCCNVG,NPM,IDSTRG,JFRWRD,JBKWRD,NMESH,MESH(15),MXITER
$GESFRS, ECUPLM(18), CORDTL, OPRCOR(6), REJLVL, PCDELA, TH$CON, JFRPBK

INTEGER SIOT, RC, WT, PARCAL, PARCON, PARCP
LOGICAL NPM, OPRCOR
LOGICAL MIDCYC

INTEGER*2 CYCNUM, CYCRNG, CYCX5, CYCRMX
COMMON/RCRDAT/DYDW(3,15), DYUP(3,15), GWHXS(3,15), CYCX5(15),
& CYCRMX(15), CYCNUM(18,15), CYCRNG(2,270), ICNO(15), GWHOLD(15), MWD(15)

LOGICAL TSY(18,15), TEY(18,15), INSTAT(15), MWMIN(15), MWMAX(15), MIDCYC(15)

COMMON/KC/KC(KC(1)/KC/KC(1)/KC/KC(1)
COMMON/KIX/KIX(KI(1))
INTEGER*2 LSTIM(270)

REAL*8 LAST, NUCL(100), RTC, IMPLS, IMP, CRIT
LOGICAL CNVCD, OPTRCH

INTEGER NECHAL(18)/18*1/

IF ($LAST .GT .0.0D) GO TO 5

KIX=APIN
KQX=NPOT
KQ1X=7
KQ2X=NPOT
KQ3X=NPIN
KQ4X=MXARCS
KQ5X=MXNODS
ITER0=0
MESHNO=0
CMESH=-1
GWHCNV=-1

$CRIT=1.E3*TH$CON
CALL ERASE(LSTIM, NCYCT/2)

5 $LAST=1.0D0

IMPLS=$LAST

CPTRCH=.FALSE.

10 CALL GOKMAN

CALL ARCPRT(0)

CALL CALSHIP
ITERTO=ITERTO+1
ITER=MOD(ITERTO-1,100)+1
$NUCL(ITER)=1.050
CNVGC=.TRUE.
DO 20 C=1,NCYCT
   IF(IABS(KX(C)-LSTIM(C)).GT.GWHCNV) CNVGD=.FALSE.
      LSTIM(C)=KX(C)
   NARCTP=PARCAL
      IF(.NOT.CNVGC.AND.GMES GT 0) GO TO 50
   NARCTP=PARCON
      IF(MESHNO.LT.NMESH) GO TO 40
      CPTRCH=.TRUE.
      WRITE(WT,902)
20  $NUCL(ITER)=-$NUCL(ITER)
      WRITE(WT,501) (I,$NUCL(I),I=1,ITER)
      CALL ARCPRT(PARCON)
      RETURN
40  MESHNO=MESHNO+1
      CMESH=MESH(MESHNO)
      GWHCNV=(PCONVG+0.001)*GMESH*0.01
      $LAST=1.050
      $TRPLS=$LAST
50  CALL ARCPRT(NARCTP)
      $=0.000
C
   ERASE OLD MARGINAL CCSTS
   LFRS=LOC(2,1,1,1)
   NZERO=IAUX*NCYCT
   CALL ERASE(KC(LFRS),NZER,CU(LFRS),NZERO,KL(LFRS),NZERO)
   DO 60 NR=1,NRCRS
      CALL SETELE(NR,GMESH)
      IDNUM=IDNO(NR)
      NCYCIN=CYCRMX(NR)
      IF(.NOT.MIDCYC(NR)) NCYCIN=NCYCIN+1
      NCYCXS=CYCXS(NR)
      ECHCV=GWHOLC(NR)
      CALL INCCRE(IDNUM,NCYCIN,NCYCXS,NCYCIN+NCYCXS,TSY(1,NR),TEY(1,NR),
CALL NEWMRG(NR,GMESH)
IF(PVY, NE, PVRATE) CALL CPERR('CONVRG',10)
IF(YBS, NE, YBASE) $=*$PVYPER$(*YBASE,YBS)
$NUCL(ITER)=$1.03*RCFACT
WRITE(WT,900) ITER,$NUCL(ITER)
$IMP=$LAST-$NUCL(ITER)
IF(($IMP.GT.$CRIT.OR.$IMPLS.GT.$CRIT).ANC.$IMP.GT.0.OD) GO TO 7C
CALL OPERR('CONVRG',5)
$LAST=$NUCL(ITER)+0.01CO
$IMPLS=$IMP
GO TO 25
70 $LAST=$NUCL(ITER)
$IMPLS=$IMP
IF(ITER.TC.LT.MXITER) GO TO 10
CALL OPERR('CONVRG',7)
    FAKE 'IF' AND 'RETURN' TO AVOID COMPILATION WARNING MESSAGE
IF(.TRUE.) GO TO 30
RETURN
900 FORMAT('SYSTEM NUCLEAR COST AT ',I3,' TH ITERATION =',-3PF15.3,
$                 $ THOUS. P.V.dollars')
901 FORMAT(' SYSTEM NUCLEAR COST AT ',I3,' TH ITERATION =',-3PF15.3,
$                 $ THOUS. P.V.dollars')
902 FORMAT('1'/'0',*,*,* * * TRUE OPTIMUM REACHED FOR GIVEN ARC
$                $ CONSTRANTS * * * */0/*/
END
SUBROUTINE CALSHP
CALCULATES SHAPE PARAMETERS FOR EACH PERIOD
SYSOPT VERSION 12-16-72
IMPLICIT INTEGER(CG)
REAL*8 RCFACT,SGTITL
COMMON/OPTLIM/RDFACT,SGTITL(10),ELAME(40,18),PVRATE,YBASE,YSTART,
$IAUX,IAUXM,NRCRS,NCYCT,NPERS,NPERSP,NPERIN,ITER,MXESX2,MXRCYC,
$MXNPER,MXRCS,MXNJD,SXARC,SIOI,APIN,APCT,RC,WT,PARCAL,PARCON,
$PARCO,PCCNVG,NPM,ICSTRG,JFRWRD,JBKWRD,NMESH,MESH(15),MXITER
$GESFRS,ECUPLM(18),CORDTL,PRCOR(6),REJLVL,PCDELA,TH$CON,JFRPBK

INTEGER SIO,RT,WT,PARCAL,PARCON,PARCOP
LOGICAL NPM,PRCOR

LOGICAL MIDCYC
INTEGER*2 CYCNUM,CYCRNG,CYXS,CYCRMX
COMMON/RCDAT/DYDWN(3,15),DYUP(3,15),GWHXS(3,15),CYXS(15),
$CYCRMX(15),CYCNUM(18,15),CYCRNG(2,270),ICTNO(15),GWHOLD(15),MWD(15)
$TSY(18,15),TEY(18,15),INSTAT(15),MWHIN(15),MWHAX(15),MIDCYC(15)
$DYHOLD(15),TOY(13,15)
CCMCN/KX/KX(1)
CCMCN/DPERMS/S(100,15),ALPHA(100,15),BETAP(100,15),FINVAR(100)
INTEGER*2 S
CCMCN/SHPINF/SLNCRT(1)),SLNWSR(100),ITRSHP,PDWSBD(100)
LOGICAL PDWSBD
REAL LR
REAL*8 SKL,SKL2
L=LOC(4,1,1,1)-1
DO 40 NP=1,NPERS
L=L+1
LCK=L-NPERSP
SKL=0.0
SKL2=0.0
MWDCT=0
DO 20 NR=1,NRCS
LCK=LOK+NPERSP
IF(S(NP,AR).NE.2) GC TC 20
KR=MWD(NR)
MWDCT=MWDCT+KR
LR=KX(LOK)*ALPHA(NP,NR)-BETAP(NP,NR)
SKL=SKL+KR*LR
SKL2=SKL2+KR*LR*LR
20 CONTINUE
SLNWSR(NP)=SKL2/MWDCT-(SKL/MWDCT)**2
40 SLNCRT(NP)=FINVAR(NP)-SLNWSR(NP)-REJLVL
RETURN
END
SUBROUTINE ARCPRT(ITYPE)

PRINTS ARCS THROUGH TYPE ITYPE

SYOPT VERSION 12-16-72

IMPLICIT INTEGER(C,G)

REAL*8 RDFACT,SGTITL

COMMON/OPTLIM/RDFACT,SGTITL(10),ELAME(40,18),PVRATE,YBASE,YSTART,
$IAUX,IAUXM,NCYC,NPERS,NPERSP,NPERIN,ITER,MXEXS2,MXARCYG,
$MNPER,MXPCLS,IXNODS,IXARCS,SIOT,NPCT,WD,PARCAL,PARCON,
$PARCOP,PCONVQ,NPM,IDSTRG,JFRWRD,JBKWRD,NMESH,MESH(15),MXITER

$,GESFRS,ECUPLM(18),CCRTCTL,CPRCUT(6),REJLVL,PCDELAA,TH$CON,JFRPBK

INTEGER SIOT,WD,PARCAL,PARCON,PARCOP

LOGICAL AFM,OPRCOR

LOGICAL POWSBD

DIMENSION DUM1(33),DUM10(33,10),DUM2(17)

EQUIVALENCE (DUM1(1),CUM10(1),DUM2(1))

REAL*8 $PARC$/$ARCS$/,$RCSB$/$CS$ ARE O*/,$DUM2

REAL*8 $COST$/

REWINO

IF(ITYPE.LE.)) RETURN
COK=.FALSE.
WRITE(WT,900)
ITER,NPICSTRG,SGTITL

READ(NPOT,903) DUM2
WRITE(WT,903) DUM2
IF(DUM2(1).EQ.$BARC$.AND.DUM2(3).EQ.$CCST$) COK=.TRUE.

GO TO 20

READ(NPOT,901) DUM1
WRITE(WT,901) DUM1

LLST=LOC(ITYPE+1,1,1,1)-1
IF(COK) LLST=LOC(9,0,C,C)-1
APRNT=LLST
NEXT=1
IF(LLST.LT.LOC(6,0,0,1)) GO TO 28
LTEMP=LLST
LLST=LOC(6,0,0,1)-1
NPRNT=LLST
NEXT=0
GO TO 28
22 WRITE(WT,904)
   CO 26 NP=1,NPERS
   READ(NPOT,901) DUM1
26 WRITE(WT,905) (DUM1(I),I=1,27),SLNCRT(NP),SLNWSR(NP)
   NPRNT=LTEMP-(LLST+NPERS)
   LLST=LTEMP
   NEXT=1
28 N10=NPRNT/10
   N1=NPRNT-N10*10
   IF(N1.LT.1) GO TO 4C
   CO 30 N=1,N1
   READ(NPOT,901) DUM1
30 WRITE(WT,901) DUM1
40 IF(N10.LT.1) GO TO 6G
   CO 50 N=1,N10
   READ(NPOT,901) CUM10
50 WRITE(WT,901) DUM10
60 IF(NEXT.EQ.0) GO TO 22
   LLSTX=LOC(9,0,0,0)-1
   NSKIP=LLSTX-LLST
   IF(NSKIP.GT.0) READ(NPOT,902) (X,I=1,NSKIP)
70 READ(NPOT,901,END=80) DUM1
   WRITE(WT,901) DUM1
   GO TO 70
80 IF(OK) CALL OPERR('ARCPRT',11)
   REWIND NPCT
   RETURN
900 FORMAT('1I'/'QITER =',I4,5X,'NPM+IDSTRG =',L2,I7,5X,
   'STRATEGY TITLE : ',1H',10A7,1H')
901 FORMAT(1X,33A4)
902 FORMAT(A4)
903 FORMAT(1X,16A8,A4)
F04 FORMAT( '+' , TI14 , 'SLNCRG' , 5X , 'SLNWSR' )
F05 FORMAT( 1X , 27A4 , F11.6 , F12.6 )

ENC

SUBROUTINE SETELE( NR , CMESH )
SETS UP NEW ELAME FOR INPUT TO INCORE

C

SYSOPT VERSION 12-16-72

IMPLICIT INTEGER( C , G )
REAL*8 RFACCT , SGTITL
COMMON/ OPTLIM / RFACCT , SGTITL( 10 ) , ELAME( 40 , 18 ) , PVRATE , YBASE , YSTART ,
$IAUX , IAUXM , NPCRS , NCYCT , NPERS , NPERSP , NPERIN , ITER , MXESX2 , MXRCYC ,
$MNPER , MXRCRS , MXNODS , MXARCS , SIOT , NPIN , NPOT , RD , WT , PARCAL , PARCON ,
$PARCO , PCUNVG , NPM , IDSTRG , JFRWRD , JBKWRD , NMESH , MESH( 15 ) , MXITER
$GESFR , ECUPLM( 18 ) , CORDTL , CPRCOR( 6 ) , REJLVL , PCDELA , TH$CON , JFRPBK

INTEGER SIOT , RD , WT , PARCAL , PARCON , PARCO
LOGICAL NPM , OPRCOR
LOGICAL MIDCYC
INTEGER*2 CYCNUM , CYCRNG , CYCX , CYCRMX
COMMON/ RCRDAT / DYDWN( 3 , 15 ) , DYUP( 3 , 15 ) , GWHXS( 3 , 15 ) , CYCX( 15 ) ,
$CYCRMX( 15 ) , CYCNUM( 18 , 15 ) , CYCRNG( 2 , 270 ) , INNO( 15 ) , GWHOLD( 15 ) , MWD( 15 )
$ , TSY( 18 , 15 ) , TEOY( 18 , 15 ) , INSTAT( 15 ) , MWMIN( 15 ) , MWMAX( 15 ) , MIDCYC( 15 )
$ , DYHCLD( 15 ) , TOY( 13 , 15 )
COMMON/ KC / KC( 1 ) / KU( 1 ) / KL( 1 )
COMMON/ KX / KX( 1 )
DATA FAKE / 0.03 /
INTEGER RC
CALL ERASE( ELAME , MXESX2*MXRCYC )
IC=0
IF( MIDCYC( NR ) ) GO TO 10
IC=1
ELAME( 1 , 1 ) = FAKE
10 CLIM = CYCRMX( NR )
CO 20 RC=1 , CLIM
CYC=CYCNUM( RC , NR )
CHAL=KX( CYC )
MIN = KL( CYC )
MAX = KU( CYC )
IGMIN=GBAL/GMESH-IAUXM/2
IL0=MAXO(MIN/GMESH,IGMIN,1)
IHI=MINO((MAX-1)/GMESH+1,IGMIN+IAUXM)
IC=IC+1
ELAME(1, IC)=GBAL
DO 20 I=IL0,IHI
20 ELAME(2*(I-IL0)+3, IC)=I*GMESH
NCYCXS=CYCXS(NR)
IF(NCYCXS.LT.1) GO TO 40
DO 30 I=1,NCYCXS
IC=IC+1
30 ELAME(1, IC)=GWHXS(I, NR)
RETURN
END

SUBROUTINE NEWMPR(NR,GMESH)
ALTERS NETWORK ARCS OF TYPE 2 & 3 FOR NEW SET OF MARGINAL COSTS
C
SYSOPT VERSION 12-16-72
IMPLICIT INTEGER(C,G)
REAL*8 RDFACT,SGTITL
COMMON/OPTLM/RDFACT,SGTITL(10),ELAME(40,18),PVRATE,YBASE,YSTART, $IAUX,IAUXM,NRCRS,NCYCT,NPERS,NPERSP,NPERIN,ITER,MXESX2,MXRCYC, $MXNPER,MXRCRS,MXNUSD,MXARCS,SIOT,NPIN,NPCT,WD,WPCAL,PARCON,
$PARCCP,PCCPVG,NFM,ISTRG,JFRWRO,JBKWRD,NMESH,MESH(15),MXITER
$,GESFRS,ECUPLM(18),CCRDTL,CPROR(6),REJLVL,PCDELA,TH$CON,JFRPBK
INTEGER SIOT,RD,WT,PARCOL,PARCON,PARCOP
LOGICAL KPM,OPROR
LOGICAL MIDCYC
INTEGER*2 CYCNUM,ICYCNG,CYCXS,CYCRMX
COMMON/RCRDAT/DYDNS(3,15),DYUPS(3,15),GWHXS(3,15),CYCXS(15), $CYCRMX(15),CYCNUM(18,15),ICYCRNG(2,270),ICNO(15),GWHOLD(15),MWD(15)
$,TSY(18,15),TEY(18,15),INSTAT(15),MWIN(15),MWMAX(15),MIDCYC(15)
$,DYHOLD(15),TOY(18,15)
COMMON/KC/KC(1)/KU/KU(1)/KL/KL(1)
INTEGER RC
IC=1
IF(MIDCYC(NR)) IC=0
CLIM = CYCRMX(NR)
DO 60 RC = 1, CLIM
IC = IC + 1
L = LCC(2, NR, RC, 0)
C TYPE 2 BASE POINT
GBAL = ELAME(I, IC)
KU(L) = GBAL
KL(L) = KU(L)
KCC = -10000
C TYPE 3 INCREMENTS
L = LCC(3, NR, RC, 0) - 1
LIM = ECUPLM(IC)
IF(LIM .LE. 0) LIM = 1000000
IF(GBAL .GT. LIM) CALL OPPER('NEWMRG', 13)
NARC = -1
DO 10 I = 3, MXE2, 2
G = ELAME(I, IC)
IF(G .LE. 0) GO TO 30
NARC = NARC + 1
IF(LIM .LE. G) GO TO 20
10 CONTINUE
GO TO 30
20 ELAME(I, IC) = LIM
30 DO 60 I = 1, NARC
ILAM = I + I + 2
LI = L + I
KC(LI) = 1000. * ELAME(ILAM, IC) + 0.5
IF(KC(LI) .LT. KCC) CALL CPERR('NEWMRG', 5)
KCO = KC(LI)
CLC = ELAME(ILAM - 1, IC)
GUP = ELAME(ILAM + 1, IC)
CDEL = GUP - GL0
IF(GBAL .GT. GUP) GO TO 50
IF(GBAL .LT. GL0) GO TO 40
KU(LI) = GUP - GBAL
KL(LI) = GLC - GBAL
GO TO 60
40  KU(LI) = GDEL
GO TO 60
50  KL(LI) = -GDEL
60) CONTINUE
RETURN

FUNCTION PVPER$(T, TBASE)
C  CALCULATE PRESENT VALUE AT TIME T OF 1$ AT TIME TBASE
C  SYSOPT VERSION 12-16-72
REAL*8 PVPER$, LN1PX
FVPER$ = DEXP(-LN1PX*(T-TBASE))
RETURN
ENTRY PVINIT(PV_RATE)
C  PRE-Calculate Log CF (1+X) in Units of Inverse Years
LN1PX = DLOG(1.0+PV_RATE)
FVINIT = LN1PX
RETURN
END

SUBROUTINE CHKSHP(SHPSEC)
C  Checks Shape Criteria To Evaluate Feasibility
C  SYSOPT VERSION 12-16-72
IMPLICIT INTEGER(C, G)
REAL*8 RDFACT, SGTITL
COMMON/OPTLIM/RDFACT, SGTITL(10), ELEAME(40, 18), PV_RATE, YBASE, YSTART,
$IAUX, IAU XM, NCRS,NCYCT,NPERS,NPERSP,NPERIN,ITER,MXESX2,MXRCYC,
$MXNPERS, MXCRS, MXNODS, MXARGS, SIO T, NP IN, NP CT, RD, WT, PARCAL, PARCON,
$PARCCP, PCONVG, NPM, IDSTRG, JFRWRD, JBKWRD, NMESH(MESH(15)), MXITER
$GESFRS, ECUPLM(18), CORDTL, OPTCOR(6), REJLVL, PCDELA, TH$CON, JFRP BK
INTEGER SIO T, RC, WT, PARCAL, PARCON, PARCCP
LOGICAL NPM, OPTCOR
COMMON/KC/KC(1)/KU/KU(1)/KL/KL(1)
COMMON/KK/KK(1)
COMMON/SHPINF/SLNCR T(100), SLNWSR(100), ITRSHP, PCWSBD(100)
LOGICAL PWSED
DIMENSION DELTAL(100)
LOGICAL SHPSOK, PCDCK
INTEGER KSTHL(20)
PCDCK = PCDELA * GT1.
LFRS = LOC(3, 1, 1, 1)
LJFRS = LOC(7, 1, 1, 1)
NZERO = IAUXM * NCYCT
CALL ERASE(KC(LFRS), NZERC, KL(LFRS), NZERO, KL(LFRS), NZERO)
C
SET UP ARCS TO ATTEMPT MINIMIZING SHAPE CRITERIA
LAUX = LFRS - IAUXM
DO 10 NC = 1, NCYCT
LAUX = LAUX + IAUXM
K(LNCYCT + NC) = KX(NC)
KU(LNCYCT + NC) = KX(NC)
K(LAU X) = 10000
KU(LAU X) = 100000
KC(LAU X + 1) = -10000
LAUX = LJFRS - 1
DO 15 NP = 1, NPERS
DO 15 NR = 1, NRCRS
DO 15 J = 1, JFRPBK
LAUX = LAUX + 1
15 KC(LAU X) = KSTHL(J)
ITRSHP = ITRSHP + 1
WRITE(WT, 905) ITRSHP
CALL DCKPAN
CALL ARCPRT(0)
CALL CALSFH
SHPSCK = .TRUE.
DO 20 NP = 1, NPERS
DELTAL(NP) = 1. * E50
IF(SLNCRT(NP) .GE. 0.) GO TO 20
SHPSCK = .FALSE.
PDWBD(NP) = .TRUE.
DELTAL(NP) = SQRT(-SLNCRT(NP))
IF(PCDOK) CALL SQUEEZ(NP, PCDELA * DELTAL(NP) * 0.01)
20 CONTINUE
IF (PARCOP.GE.4) CALL ARCPRT(PARCOP)
WRITE(WT,906) ITRSHIP
WRITE(WT,910) (SLNCRT(N),N=1,NPERS)
IF (SHPSOK) GO TO 40
WRITE(WT,920) (DELTAL(N),N=1,NPERS)
WRITE(WT,930)
IF (PCDCK) GO TO 40
WRITE(WT,940) PCDELA
GC TC 40
ENTRY ONLY$
ITRSHIP=0
LJFRS=LOC(7,1,1,1)
LAUX=LJFRS-1
CO 30 J=1,JFRPBK
35 KDLC=LOC(7,1,1,1)
30 KSTHL0(J)=KC(LAUX+J)
35 PDWSBD(NP)=.FALSE.
40 NZERO=JFRPBK*NRCRS*NPERS
CALL ERASE(KC(LJFRS),NZERO)
RETURN
905 FORMAT('1',/,'2',T20,'** * * * ENTERING SHAPE ITERATION NUMBER',
& $ 14,' ** * * *')
906 FORMAT('1',/,'2',T20,'** * * * RESULTS FOR SHAPE ITERATION NUMBER'
& $ 14,' ** * * *')
91) FORMAT('C',/,'0' SLNCRT(NP), NP=1,NPERS :/(1F10.6))
920 FORMAT('C',/,'0' DELTAL(NP), NP=1,NPERS :/(1DF10.6))
530 FORMAT('C',/,'0' T20,'SHAPE CRITERION REQUIRES ANOTHER OUTER ITERATION'
& $1CN')
940 FORMAT('0',/,'0X',/,'T20','SHAPE CRITERION REQUIRES ANOTHER OUTER ITERATION'
& $1CN')
END
SUBROUTINE SQUEEZ(NP,CEL)
CALL SQUEEZES PERIOD CAPACITY FACTOR RANGE BY CEL CA BOTH ENDS
C SQUEEZES PERIOD CAPACITY FACTOR RANGE BY CEL CA BOTH ENDS
C SYSOPT VERSION 12-16-72
IMPLICIT INTEGER(C,G)
REAL*8 RDFACT, SGITL
CCMMCN/OPTLIM/RDFACT, SGITL(10), ELAME(40,18), PVRATE, YBASE, YSTART,
$IAUX, IAUXM, NRCRS, NCYCT, NPER, NPERSP, NPERIN, ITER, MXEX2, MXRCYC,
$MNXPER, MXRCS, MXNODS, MVARCS, SIOT, NPIN, NPCP, RD, BT, PARCAL, PARCON,
$PARCOP, PCONV, NPM, IDSTRG, JFRW, JKWRD, NMSH, MESH(15), MXITER
$GESFRS, ECUPLM(18), CORCTL, OPKOR(6), REFLVL, PCDELA, TH$CON, JFRPBK
INTEGER SIOT, RD, BT, PARCAL, PARCON, PARCOP
LOGICAL NPM, OPKOR
CCMMCN/KC/K(1)/KU/KU(1)/KL/KL(1)
COMMON/PDFERM/S(100,15), ALPHA(100,15), BETAP(100,15), FINVAR(100)
INTEGER*2 S
CCMMCN/SHPINF/SLNCR(100), SLNWSR(100), ITRRHP, PDWSBD(100)
LOGICAL PDWSBD
REAL LM, LMN
DO 66 NC NR=1, NRCRS
A=ALPHA(NP, NR)
B=BETAP(NP, NR)
LJFRS=LOC(7, NR, 0, NP)
IF(KU(LJFRS) .LE. 0) GO TO 60
LAUX=LJFRS-1
KFMN=0
KFMX=0
DO 20 J=1, JFRPBK
LAUX=LAUX+1
KFMN=KFMN+KL(LAUX)
KFMX=KFMX+KU(LAUX)
20 LMN=LMN+1
LIN=LOC(4, NR, 0, NP)
KIMN=KL(LIN)
KIMAX=KU(LIN)
KAMN=MAX(KFMN, KIMN)
KAMAX=MIN(KFMX, KIMAX)
LMAX=A*KAMAX-B
LMIN=A*KAMN-B
CEL=AMIN1(DEL, (LMAX-LMIN)/3.)
LMAX=LMAX-DEL
LMIN=LMIN+DEL
FLACE NEW CONSTRAINTS CN ARCS

MOX=(LMAX+B)/A
MON=(LMIN+B)/A+0.5
MXD=KF MAX-MOX
MND=MON-KFMIN
LFRS=LOC(7,NR,0,NP)
LAUX=LFRS

JF=1
30 JF=JF+1
IF(JF.GT.JFRWRD) GC TC 40
LAUX=LAUX+1
MW=KL(LAUX)
IF(MXD.LT.MW) GO TC 35
KU(LAUX)=0
MXD=MXD-Mw
GO TO 30
35 KU(LAUX)=MW-MXC
40 LAUX=LFRS+JFRPBK
JB=JBKWRD+1
50 JB=JB-1
IF(JB.LT.1) GO TO 60
LAUX=LAUX-1
MW=-(KL(LAUX))
IF(MND.LT.MW) GO TO 55
KL(LAUX)=0
MND=MND-Mw
GO TO 50
55 KL(LAUX)=-(MW-MND)
60 CONTINUE
RETURN
END

SUBROUTINE EDTSFP(SHPSOK)
EDITS SHAPE INFO. AND PRINTS FINAL ALTERED ENERGY LIMITS

C SYSUPT VERSION 12-16-72
IMPLICIT INTEGER(C,G)
REAL*8 RCFACT,SGTITL
COMMON/OPTLIM/RCFACT,SGTITL(10),ELAME(40,18),PVALT,YBASE,YSTART,$IAUX,IAUX*,NRCRS,NCTP,NPERS,NPERS,PNERI,ITER,MXESX2,MXRCYC,$MXPER,MXARC,MXNODS,MXARC,SIO,NPCT,WRD,TAR,PARCAL,PARCON,$PARCP,PCCNVG,NPM,ICSTRG,JFRWD,JKWND,NMESH,MESH(15),MXITER,$GESFRS,ECUPLM(18),CCRTL,CPRCOR(6),REJLVL,PCDEL,TH$CON,FRPBK
INTEGER SIOT,ND,W,WRD,TAR,PARCAL,PARCON,PARCP
LOGICAL NPM,CPRCOR
COMMON/KC/KC(1)/CU/KU(1)/KL/KL(1)
COMMON/SHPINF/SLNCR(100),SLNWSR(100),ITRSP,PDWSBD(100)
LOGICAL PDWSBD
LOGICAL SHPSOK
CATA STAR/*/ /,$NCT/'NCT '/
WORD=STAR
IF(.NOT.SHPSOK) WORC=$NOT
KEY=0
IF(ITRSP.EQ.1) KEY=2
WRITE(WT,910) KEY,ITRSP
IF(KEY.EQ.2) WRITE(WT,920)
WRITE(WT,911) WORD
IF(KEY.EQ.2) RETURN
WRITE(WT,930)
CO 80 NP=1,NPEPS
IF(.NOT.PDWSBD(NP)) GC TC 8)
WRITE(WT,900)
CO 60 NR=1,NRCRS
LJRS=LOC(7,NR,0,NP)
LAUX=LJRS-1
KFMIN=0
KFMAX=0
CO 20 J=1,JFRPBK
LAUX=LAUX+1
KFMIN=KFMIN+KL(LAUX)
KFMAX=KFMAX+KL(LAUX)
LIN=LOC(4,NR,0,NP)
KMIN=KL(LIN)
KIMAX=KL(LIN)
KFIN = MAXO(KFIN, KMIN)
KMAX = MINQ(KMAX, KIMAX)
KFDEL = KFMAX - KFIN
KIDEL = KIMAX - KMIN
FCDEL = KFDEL * 100. / (KIDEL + 1.E-20)
IF(KUL(JFRES) .LE. 0) PCDEL = 0.0
60 WRITE(WT,940)NP,NR,KIMAX,KMIN,KIDEL,KFMAX,KFIN,PCDEL,KFDEL,PCDEL
80 CONTINUE
RETURN
900 FORMAT('C')
910 FORMAT('I1/I1,T20,'* * * * * ',I4,' SHAPE ITERATIONS WERE REQUI
911 FORMAT('C',T20,'* * * * ','A4,' ALL FINAL SHAPES MET SHAPE CRIT
920 FORMAT('C',T20,'* * * * ','A4,' THEREFORE, NC PERIODS WERE ALTERED * * * * *
930 FORMAT('O',T40,'10X','PERIOD REACTOR INIT.MAX INIT.MIN INIT.DEL FINL.MAX F
940 FORMAT(15,18,3I10,3X,3I10,F12.1)
END
SUBROUTINE OPTMUM(CPTRCH,$NKPRD)
C SUPERVISES PRINTING OF OPTIMUM SOLUTION
C SYLOPT VERSION 12-16-72
C IMPLICIT INTEGER(C,G)
REAL*8 RDFACT,GFTIL
COMMON/OPTLIM/RDFACT,SGTIL(10),ELAME(40,18),PVRATE,YBASE,YSTART,
$IAUX,IAUXM,NCRCS,NCYCT,NPERS,NPERSP,NPERIN,ITER,MXESX2,MXRCYC,
$MXNPER,MRXCRS,MXNODS,MRARC,SIOT,NPIN,RPIN,RPIN,RC,PT,W,PARCAL,PARCON,
$PARCOP,PCONVG,NPM,IPSTRG,IFRWRD,IBKWRD,NMESH,MESH(15),MXITER
$GESFRS,EUPGME(18),CGRS,CPGRCR(6),REJLVL,PCDELA,THECON,JFRPBD
INTEGER SIOT,RC,WT,PARCAL,PARCON,PARCOP
LOGICAL NPM,CPGRCR
LOGICAL MDDCVC
INTEGER CYCNUM,CRYPT,CYCXS,CRYPT
COMMON/RCRDAT/DYDWN(3,15),DYUP(3,15),GWHXS(3,15),CYCXS(15),
$CRYPT(15),CYCNUM(18,15),CRYPT(2,270),ICNO(15),GWHOLD(15),MWD(15)
$T SY(18, 15), T EY(18, 15), I N S T A T (15), M W M I N (15), M W M A X (15), M I D C Y C (15)
$D H O L D (18, 15), TO (18, 15)
COMMON/FINALS/S4, SA4, SP4, SL4, SP8
REAL*8 S4(13), SA4(13), SP4(13), SL4(13), SP8(13)
COMMON/PRINTS/RELCST, INCCST, BALCST, NBLCST, PIRDAT, PBATCS, KRD, KWT
LOGICAL RELCST, INCCST, BALCST, NBLCST, PIRDAT, PBATCS
INTEGER NECR(18)/18*1/
REAL*8 $NKPRD, $DEL, WORD, $FORC$/'FORCED'/$, $TRUE$/' TRUE'/$, $RTC
LOGICAL OPTRCHST, STORE(6), USE(6)
EQUIVALENCE (USE(1), RELCST)
CO 10 I=1, 6
STORE(I)=USE(I)
10 USE(I)=OPRCOR(I)
IF(CORDTL.LE.0) GO TO 30
IF(OPRCOR(3).OR.OPRCOR(4).OR.OPRCOR(5).OR.OPRCOR(6)) GO TO 20
GO TO 30
20 CHUCE=10**6
$=0.00D0
DO 28 NR=1, NRCS
CALL SET ELE(NR, GHUGE)
DO 26 I=1, MRCYC
26 ELAME(3, I)=0.0
IDNUM=IDNC(NR)
NCYCIN=NCYCMX(NR)
IF(.NOT. MIDCYC(NR)) NCYCIN=NCYCIN+1
NCYCS=NCYX(NR)
ECHDOV=GWHOLD(NR)
CALL INCCRE(IDNUM, NCYCIN, NCYCS, NCYCIN+NCYCS, TSY(1, NR), TEY(1, NR), $NECRAL, ELAME, MXESX2, ECHDOV, RTC, PVR, YBS, ECUPL, TOY(1, NR))
$=#+RTC
$NKPRD=#*. C3*RDFACT
30 DO 40 I=1, 6
40 USE(I)=STORE(I)
IF($NKPRD.GE.1.02) GC TO 2)
$DEL=$NKPRD-SP8(3)
SP8(2)=SP8(2)+$DEL
SP8(3)=SP8(3)+$DEL
SP8(8)=SP8(8)+$DEL
SP8(9)=SP8(9)+$DEL
SP8(12)=SP8(12)+$DEL
WORD=$FORC$
IF(OPTRCH) WORD=$TRUE$
WRITE(WT,904) NPM, IDSTRG, SG TITL
WRITE(WT,901) WORD, $NKPRD
WRITE(WT,907)
WRITE(WT,908)(S4(I),I=2,13),(SA4(I),I=2,13),(SP4(I),I=2,13),
$(SL4(I),I=2,13)
WRITE(WT,909) YBASE
WRITE(WT,910)(SP8(I),I=2,12)
WRITE(WT,902) WORD, SP8(12)
RETURN
901 FORMAT('0'/0',T20,'AT ',A6,' OPTIMUM, $NKPRD = ',-3PF15.3,
$' THOUS. P.V. DOLLARS'/"0")
902 FORMAT('0'/0',T20,'AT ',A6,' OPTIMUM, TCTAL SYSTEM COST = ',
$' THOUS. P.V. DOLLARS'/"0")
904 FORMAT('1'/'0'/,1X, 'STRATEGY TITLE : ',U13,10A7,1H)
907 FORMAT('0'------------ MEGAWATT-HOURS ELECTRIC ----------)
$4X,'PERIOD MWINST MWONLN MWPEAK MWMRGN MWSPIN PLOFL',
$4X,'EXPDEM EXPGEN XNKGEN XNNGEN EXPEMR UNSRVD'
908 FORMAT('0'TOTAL :',5F8.0,F8.4,6F11.2/
$ '0AVG. :',5F8.0,F8.4,6F11.2/
$ '0PV/0AVG. :',5F8.0,F8.4,6F11.2/
$ '0LVAVG. :',5F8.0,F8.4,6F11.2/
909 FORMAT('0'/0',T20,'ALL COSTS IN THOUSANDS OF DOLLARS PRESENT VALU
$ED TO YBASE = ',F9.4,' YEARS'/
$ 'PERIOD PRCD$ $NKPRD $NNPRD SUSD$ $NKS
$US $NASUS $SBTCT $NKTOT $NNTOT EMRP$ TCTA
$L$/)
910 FORMAT('CPVTOTL :',-3PF15.3)
FUNCTION LOC(ITYPE,R,C,P)
C CALCULATES LOC AS PCINTER TO DESIRED ARC
C SYSOPT VERSION 12-16-72
IMPLICIT INTEGER(C,G)
REAL*R,RFAC,T,SGTITL
COMMON/OPTLIM/RDFACT,SGTITL(10),ELAME(40,18),PVRATE,YBASE,YSTART,
$IAUX,IAUXM,NRCRS,NCYCT,NPERS,NPERSP,NPERIN,ITER,MXEXX2,MXRCYC,
$MXNPEN,MRXCRS,MXNODS,MXARCST,SIOT,NPIN,NPCRT,RC,W,PARCAL,PARCON,
$PARCOP,PCONVG,NPM,ICSTGR,JFRWRD,JBKWRT,NUMESH,MES(15),MXITER
$,GEFSRS,ECUPLM(18),CORDTL,CPRCOR(6),REJLVNL,PCDELA,TH$CON,JFRPBK
INTEGER SIOT,RD,WT,PARCAL,PARCON,PARCOP
LOGICAL NPM,OPRCOR
LOGICAL MDCYC
INTEGER*2 CYCNUM,CYCRNG,CYCXS,CYCRMX
COMMON/RCDAT/DYOWN(3,15),CYUP(3,15),GWHXS(3,15),CYCXS(15),
$CYCRMX(15),CYCNUM(18,15),CYCRNG(2,270),ICNO(15),GWHOLD(15),MWD(15)
$TSY(18,15),TEY(18,15),INSTAT(15),MMAXX(15),MWMINX(15),MDCYC(15)
INTEGER R,C,P
GO TO (1,2,3,4,5,6,7,8,9,10),ITYPE
1 LOC=CYCNUM(C,R)
RETURN
2 LOC=LOC1*X+CYCNUM(C,R)
RETURN
3 LCC=LOC2*X+(CYCNUM(C,R)-1)*IAUXM+1
RETURN
4 IF(P.GT.NPERS) GO TO 44
LOC=LOC3*X*(P-1)*NPERSP+P
RETURN
44 LCC=LOC3*X*R*NPERSP
RETURN
5 LOC=LOC4*X+1
RETURN
6 LOC=LOC5*X+P
RETURN
END
LOC = LOC6X + ((P-1) * NRCRS + R-1) * JT0TAL + 1
RETURN
8 CONTINUE
9 LOC = LOC9X
RETURN

C INITIALIZATION

10 JT0TAL = JFRW0RD + JBKWRC
LOC1X = NCYCT
LOC2X = LOC1X + NCYCT
LOC3X = LOC2X + IAUXM * NCYCT
LOC4X = LCC3X + NPERSP * NRCRS
LOC5X = LOC4X + 3
LOC6X = LOC5X + NPER
LOC7X = LOC6X + JT0TAL * NRCRS * NPER
LOC9X = LOC7X + 1
LOC = C
RETURN
END

SUBROUTINE OPERR(SUEFJERR)

C WRITES OUT ALL ERROR MESSAGES FOR SYSOPT

C SYSCPT VERSION 12-16-72
C IMPLICIT INTEGER(C,G)
REAL*8 RFAC0, SGTLT
COMMON/OPTLIM/RDFACT, SGTLT(10), ELAME(14), PVRATE, YBASE, YSTART,
$IAUX, IAUXM, NRCRS, NCRYCT, NPER, NPERSP, NPERIN, ITER, MXEX2, MRG3,
$MXNPER, MXRCS, MXNODS, MXARCS, SIOT, NPT, RD, WT, PARCAL, PARCON,
$PARCOP, PCONVP, NPM, IDSTRG, JFRW0RD, JBKW0RD, N0ESH, MESH(15), MLEAN
$SFRS, ECUPLM(18), CODTL, CPRCOR(6), REJVL, PCD2EL, TCON, JFRPBK
INTEGER SIOT, RD, WT, PARCAL, PARCON, PARCOP
LOGICAL NPM, OPDCOR
INTEGER ERRCD
REAL*8 SLBR, $QUIT$
DATA NPRINT /0/, $QUIT$/'QUIT'/, $ERRCD/0/, MAXERR/16777216/
C MAXERR=16**6
REAL*8 CC1(11)'/CDFMIN AND CDFMAX DATA ARE INCOSISTENT IN SOME SE
$CASE

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REAL*8 C02(11) /'MWDTOT.NE.LVMAX-LVLMIN .CR. MW.GE.PEMIN

REAL*8 C03(11) /'REACTCR GR STRATEGY ID'S DJ ACT AGREE

REAL*8 C04(11) /'NUMBER OF ARCS INPUT TO O-O-K AND ARC EQ. DO NOT A

REAL*8 C05(11) /'MARGINAL COST CURVE NOT MONOTONICALLY DECREASING

REAL*8 C06(11) /'IMPROPER INPUT SEQUENCE &/OR CARD; INPUT OPTIONS C

REAL*8 C07(11) /'MXITER REACHED WITHOUT COMPLETE CONVERGENCE

REAL*8 C08(11) /'NUMBER OF ARCS INPUT TO O-O-K AND ARC EQ. DO NOT A

REAL*8 C09(11) /'NUCL NCT CONVERGING RAPIDLY TO MINIMUM ; ASS

REAL*8 C10(11) /'INCORE AND SYSOPT USING DIFFERENT P.V.RATES

REAL*8 C11(11) /'O-C-K NETWORK SOLUTION IS TRULY OUT-OF-KILTER

REAL*8 C12(11) /'PREMATURE END TO SYSINT DATA ; SOME PERIODS NOT RE

REAL*8 C13(11) /'CYCLE ENERGY GREATER THAN ITS UPPER LIMIT

IFRF=JERR

ERRCOD=MCD(ERRCOD,MAXERR)

ERRCOD=16*ERRCOD+IERR

NPRINT=NPRINT+1

GO TO (1,2,3,4,5,6,7,8,9,10,11,12,13),IERR

1 WRITE(WT,900) SUBR,ERRCOD,C01,NPRINT

GO TO 1000

2 WRITE(WT,900) SUBR,ERRCOD,C02,NPRINT

GO TO 1000

3 WRITE(WT,900) SUBR,ERRCOD,C03,NPRINT

GO TO 1000

4 WRITE(WT,900) SUBR,ERRCOD,C04,NPRINT

GO TO 1000

5 WRITE(WT,900) SUBR,ERRCOD,C05,NPRINT

GO TO 1000

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RETURN
6 WRITE(WT,900) SUBR,ERRCOD,C06,NPRINT
   GO TO 1000
7 WRITE(WT,900) SUBR,ERRCOD,C07,NPRINT
   RETURN
8 WRITE(WT,900) SUBR,ERRCOD,NPRINT,NPRINT
   CALL ICERRS('OPERR ',8)
   STOP
9 WRITE(WT,900) SUBR,ERRCOD,C09,NPRINT
   RETURN
10 WRITE(WT,900) SUBR,ERRCOD,C10,NPRINT
   GC TC 1000
11 WRITE(WT,900) SUBR,ERRCOD,C11,NPRINT
   CC TC 1000
12 WRITE(WT,900) SUBR,ERRCOD,C12,NPRINT
   GC TC 1000
13 WRITE(WT,900) SUBR,ERRCOD,C13,NPRINT
   RETURN
1000 NPRINT=NPRINT+1
   WRITE(WT,999) NPRINT
   SUBR=$QUIT$
   IERR=8
   GO TO 10C
900 FORMAT(130(''-')/,130(''-'),12)
   | SUBR. 'A6' HAS ERRCOD = 'Z8': ',
908 FORMAT(130(''-')/,130(''-'),12)
   | SUBR. 'A6' HAS ERRCOD = 'Z8': ',
908 FORMAT(130(''-')/,130(''-'),12)
   | SUBR. 'A6' HAS ERRCOD = 'Z8': ',
968 FORMAT(130(''-')/,130(''-'),12)
   | SUBR. 'A6' HAS ERRCOD = 'Z8': ',
999 FORMAT(130(''-')/,130(''-'),12)
   | PREVIOUS ERROR SEVERE ENOUGH TO',
  | INVALIATE FURTHER COMPUTATIONS. THEREFORE,',
  | TERMINATING EXECUTION.',
  | END

RETURN
6 WRITE(WT,900) SUBR,ERRCOD,C06,NPRINT
   GO TO 1000
7 WRITE(WT,900) SUBR,ERRCOD,C07,NPRINT
   RETURN
8 WRITE(WT,900) SUBR,ERRCOD,NPRINT,NPRINT
   CALL ICERRS('OPERR ',8)
   STOP
9 WRITE(WT,900) SUBR,ERRCOD,C09,NPRINT
   RETURN
10 WRITE(WT,900) SUBR,ERRCOD,C10,NPRINT
   GC TC 1000
11 WRITE(WT,900) SUBR,ERRCOD,C11,NPRINT
   CC TC 1000
12 WRITE(WT,900) SUBR,ERRCOD,C12,NPRINT
   GC TC 1000
13 WRITE(WT,900) SUBR,ERRCOD,C13,NPRINT
   RETURN
1000 NPRINT=NPRINT+1
   WRITE(WT,999) NPRINT
   SUBR=$QUIT$
   IERR=8
   GO TO 10C
900 FORMAT(130(''-')/,130(''-'),12)
   | SUBR. 'A6' HAS ERRCOD = 'Z8': ',
908 FORMAT(130(''-')/,130(''-'),12)
   | SUBR. 'A6' HAS ERRCOD = 'Z8': ',
908 FORMAT(130(''-')/,130(''-'),12)
   | SUBR. 'A6' HAS ERRCOD = 'Z8': ',
968 FORMAT(130(''-')/,130(''-'),12)
   | SUBR. 'A6' HAS ERRCOD = 'Z8': ',
999 FORMAT(130(''-')/,130(''-'),12)
   | PREVIOUS ERROR SEVERE ENOUGH TO',
  | INVALIATE FURTHER COMPUTATIONS. THEREFORE,',
  | TERMINATING EXECUTION.',
  | END
ASSEMBLER LANGUAGE SUBROUTINE ERASE

WRITTEN BY
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TC SET ELEMENTS ARE ARRAY NAMES EXPRESSING REAL OR INTEGER ARRAYS AND N1, N2,... ARE INTEGER VALUES OR EXPRESSIONS GIVING THE ARRAY SIZES.

SUPRFUTINE CMPTIM(LV, ENT)

PRINTS TIME OF INTRA-SUBROUTINE TRANSFERS OR CATE&TIME

SYSOPT VERSION 03-06-72

"TIMING" IS AN M.I.T. INTERNAL SUBROUTINE THAT RETURNS THE CPU TIME IN HUNDREDTHS OF SECONDS.

"WHEN" IS AN M.I.T. INTERNAL SUBROUTINE THAT RETURNS THE DATE AND TIME IN THE FOLLOWING 5A4 FORMAT: MM/DD/YY HR*MI*SS.FF

DIMENSION A(5)
DOUBLE PRECISION LV, ENT
INTEGER TNOW, TSTART, TREL
 INTEGER WT
CALL TIMING(TNOW)
TREL = TNOW - TSTART
IF (TREL LT 0) TREL = TREL + 8640000
TI = TREL / 100.
WRITE(WT, 10) LV, ENT, TI
RETURN
ENTRY STRTIM(WT)
CALL TIMING(TSTART)
CALL WHEN(A)
WRITE(WT, 20) A
RETURN
10 FORMAT (/, T103, 29(*''),/), T103, '*' LV. '*' A6, T131, '*' /,
$ T103, '*' ENT. '*' A6, ' @', F7.2, ' SEC. ''' /, T103, 29(''**)' /)
20 FORMAT (/ T103, 29('''')/ T103, '*' DATE = ' ', 2A4, T131, ''''/
$ T103, '*' TIME = ' ', 3A4, T131, ''''/ T103, 25(''**)' /)
END

******************************************************************************

000000000

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I.E. - CALL ERASE(C,26*31,N,7*31,E,254)

ERASE
START 0
SAVE (14,12), *
BALR 12, 0
USING *, 12
SR 0, 0
SR 2, 2
L 6, =F'41
L 3, 0(2, 1)
L 4, 4(2, 1)
SLA 7, 2
SR 7, 6
SR 5, 5
ST 0, 0(5, 3)
BXLE 5, 6, E2
LTR 4, 4
RM RETN
A 2, =F'81
E E1
RETN RETURN (14, 12), T
END
CUT-OFF-KILTER MAIN PROGRAM

ONLY DIMENSION STATEMENTS IN THIS PROGRAM NEED BE CHANGED TO

ALTER MAXIMUM ARCS OR MAXIMUM NODES ALLOWABLE.

IF A = MAXIMUM ARCS AND N = MAXIMUM NODES,

KL, KC, KU, KX, AND JI ARE DIMENSIONED BY 'A'

NL(N), NN(2*N), NP(N), IJ(MAX(N, A-2*(N+1))), IL(N+1), JL(N+1)


DIMENSION NN(2000), NP(1000), IL(1001), JL(1001), JI(2000)

DIMENSION LC(9), KA(18,2), KQ(9)

COMMON /KL/KL/KC/KC/KU/KU/KX/KX/NL/NL/NN/NN/NP/NP/IJ/IJ/IL/IL

COMMON /JL/JL/JI/JI

COMMON /MC/MC/LC/LC/KA/KI/KQ/KI/KQ/KQ/KQ

SYSTEM INPUT DEVICE

KI=5

SYSTEM OUTPUT DEVICE

KO=6

CARD PUNCH

KQ(1)=7

RESERVED OUTPUT TAPE

KQ(2)=3

RESERVED INPUT TAPE

KQ(3)=2

MAXIMUM ARCS

KQ(4)=2000

MAXIMUM NODES

KQ(5)=1000

KQ(6)=0

IFIN=32767

CALL MAIN

END

SUBROUTINE MAIN

DIMENSION LC(9), KA(18,2), KQ(9)

COMMON /KL/KL(1)/KC/KC(1)/KU/KU(1)/KX/KX(1)/NL/NL(1)
CALL CMPTIM(' ', 'DATAIN')
CALL PRECAT(KS)
IF(KS.EQ.-1) RETURN
IF(KS.NE.0) GO TO 1
CALL ARCASY(L)
CALL MAKEJL
IF(LER.GE.KQ(4)) GO TO 88
LER=LER*KQ(8)
IF(L.EQ.0) GO TO 1
CALL NODASY
CALL REACER
CALL TRANSL
IF(LER.NE.0) GO TO 88
CALL CMPTIM(' CATAIN', 'ALGOR.')
I=C
KUP=1
KE(1C1)=C
DO 26 K=1,N
IF(KL.LE.KUP) GO TO 38
I=I+1
KUP=LDECR(IL(I+1))
26 CONTINUE
38 CALL KILTER(I)
IF(LER.EQ.0) GO TO 26
IF(LER.NE.107) GO TO 24
KE(101)=KE(101)+1
KF=KE(101)
IF(KE(101).GT.100) GO TO 26
KE(KF)=K
26 CONTINUE
C COMPLETED CHECKING ALL ARCS
LER=0
99 CALL CMPTIM('ALGOR.', 'OUTPUT')
   CALL OUTPUT(KE)
   CALL CMPTIM('OUTPUT', '')
C CYCLE BACK FOR ANOTHER RUN
   GO TO 100
24 WRITE(KO, 54)
   LL = LADDR(IJ(K))
   WRITE(KO, 55) NN(2*I-1), NN(2*I), NN(2*LL-1), NN(2*LL)
   GO TO 99
88 WRITE(KO, 56)
   STOP
   ENTRY OOKMAN
C ENTRY TO OOK FROM OTHER CODES (WHICH HAVE ALREADY CALLED STRTIM)
   COMMON/OCKCOM/KIX,KCX,KQ1X,KQ2X,KQ3X,KQ4X,KQ5X
   KI=KIX
   KO=KCX
   KQ(1)=KQ1X
   KQ(2)=KQ2X
   KQ(3)=KQ3X
   KQ(4)=KQ4X
   KQ(5)=KQ5X
   KQ(6)=J
   KQ(9)=0
   IF (IN=2767
   IF (.TRUE.) GO TO 100
   STCP
51 FORMAT(A4)
54 FORMAT(24H0OVERFLOW IN NODE PRICES)
55 FORMAT(23H0RUN TERMINATED AT ARC,4A4)
56 FORMAT(37H0RUN TERMINATED DUE TO ERRCRS IN DATA)
C***********************************************
C SUBROUTINE PREDAT(KS)
C DIMENSION LC(9), KA(18, 2), KQ(9)
COMMON/KL/KL(1)/KC/KC(1)/KU/KU(1)/KK/KK(1)/NL/NL(1)
COMMON/NN/NN(1)/NP/NP(1)/IJ/IJ(1)/IL/IL(1)/JL/JL(1)/JI/JI(1)
PAGE 3
COMMON /M/M/N/N/LER/LER/KAT/KAT/KCR/KOR/KTER/KTER
COMMON /MINE/MINE/LC/LC/KA/KA/IFIN/IFIN/KI/KI/KO/KO/KQ/KQ/K/K
INTEGER PAUSE, SAVE, READY, CARDS, TAPE, SKIP, TRANSP, ARCS, END
DATA PAUSE, SAVE, READY /4HPAUS, 4HSAVE, 4HREAD /
DATA CARDS, TAPE, SKIP, TRANSP /4HCARD, 4HTAPE, 4HSKIP, 4HTRAN /
DATA ARCS /4HARCS /
DATA END /4HEND /
WRITE(KO,93)
CALL ERASE(LC,9)
KOR=KQ(3)
KQ(7)=0
KS=0
21 READ(KI,50) (KA(I,1),I=1,18)
WRITE(KO,91) (KA(I,1),I=1,18)
IF(KA(1,1).EQ.PAUSE) GO TO 180
IF(KA(1,1).EQ.SAVE) GO TO 50
IF(KA(1,1).EQ.REASY) GO TO 100
GO TO 21
C END JOB
180 IF(KQ(6).EQ.0) GO TO 182
K2=KQ(2)
WRITE(KO,98)
END FILE K2
GO TO 183
182 WRITE(KO,99)
183 KS=-1
RETURN
C SAVE
50 K5S=1
B RETURN
C READY
100 IEA=KQ(4)
IEN=KQ(5)
IEJL=MAXO(IEN+1,IEA-2*IEN-1)
CALL ERASE(KL,IEA,KC,IEA,KU,IEA,KX,IEA,IJ,IEA,JI,IEA,
INL,IEN,NN,2*IEN,NP,IEN,IL,IEN+1,JL,IEJL)
N=0
N=3
LER=0
KQ(8)=1
3 READ(KI,90) (KA(I,1),I=1,18)
WRITE(KO,91) (KA(I,1),I=1,18)
IF(KA(1,1).EQ.CARDS) GC TO 1
IF(KA(1,1).EQ.TAPE) GO TO 6
IF(KA(1,1).EQ.SKIP) GC TO 6
IF(KA(1,1).EQ.TRANSP) GO TO 14
GO TO 3
14 KQ(8)=0
GO TO 3
6 IF(KQ(9).NE.0) GO TO 7
KQ(9)=1
REWIND KCR
7 IF(KA(1,1).EQ.TAPE) GC TO 4
GO TO 13
1 KOR=KI
4 READ(KOR,90) (KA(I,1),I=1,13)
WRITE(KO,91) (KA(I,1),I=1,18)
IF(KA(1,1).EQ.ARCS) GC TO 8
TITLE
10 KAI(I,2)=KA(I,1)
GO TO 4
13 READ(KOR,92) KA(1,1)
IF(KA(1,1).EQ.END) GO TO 3
GO TO 13
9) FORMAT(18A4)
91 FORMAT(1+018A4)
92 FORMAT(A4)
93 FORMAT(1H1)
98 FORMAT(31HRESERVED TAPE HAS BEEN WRITTEN///1HO)
99 FORMAT(34HNO RESERVED TAPE HAS BEEN WRITTEN)
SUBROUTINE ARCASY(LL)
DIMENSION LC(S),KA(18,2),KQ(9)
INTEGER KE(2),KF(2),KD(2)
COMMON/KL/KL(1)/KC/KC(1)/KU/KU(1)/NL/NL(1)
COMMON/NN/NN(1)/NP/NP(1)/IJ/IJ(I)/IL/IL(1)/JL/JL(1)/JI/JI(1)
COMMON/M/M/N/N/LER/LER/KAT/KAT/KOR/KOR/KTER/KTER
INTEGER END,NODESBLANK
DATA END,NODESBLANK/4HEND,4HNODE,4H/
LER=0
IF(KD(1).EQ.END) GO TO 1
IF(KD(1).EQ.NODES) GO TO 2
IF(KD(1).EQ.BLAN) GO TO 3
GO TO 4

NO NODES TO DO
1 LL=0
GO TO 5

NODES TO DO
2 LL=2
WRITE(KO,94) KC(1),KD(2)
5 N=N-1
IF(LER.EQ.0) GO TO 101
KQ(8)=2
101 RETURN

ARC TO FILE
3 IF(KE(1).EQ.BLAN.AND.KE(2).EQ.BLAN) GO TO 6
KQ(N)=KA(1,1)
KU(N)=KA(2,1)
KL(N)=KA(3,1)
KX(N) = KA(4,1)
IF(KE(1).EQ.KF(1).AND.KE(2).EQ.KF(2)) GO TO 9
IF(NCDENC(KE(1),KE(2)).EQ.M+1) GO TO 11
WRITE(KO,91) KE(1),KE(2),IJ(2*N-1),IJ(2*N)
GO TO 12

11 KF(1) = KE(1)
KF(2) = KE(2)
IF(M GT KQ(5)) GO TO 23
M = M+1
NN(2*M-1) = KE(1)
NN(2*M) = KE(2)
NL(M) = N

9 IF(N GT KQ(4)) GO TO 20
N = N+1
GO TO 6

4 WRITE(KO,92) N

12 WRITE(KO,93) KD(1),KD(2),KE(1),KE(2),IJ(2*N-1),IJ(2*N),KA(I,1),I=OKF01980 00K0233
11,4
LER = LER+1
GO TO 6

20 WRITE(KO,89)

25 LER = 100 J C
GO TO 99

23 WRITE(KO,88)
GO TO 25

88 FORMAT(27H0TOO MANY NCDES IN THIS RUN)
89 FORMAT(26H0TOO MANY ARCS IN THIS RUN)
90 FORMAT(3(A4,A2),2X,4110)
91 FORMAT(36H0SOURCE NODES ARE NOT ADJACENT, ARC 4A4)
92 FORMAT(36H0CARD PUNCHING ERROR IN ARC CARD NC.,16)
93 FORMAT(1H03M (A4,A2),2X,4110)
94 FORMAT(1H03M (A4,A2)
END

C********************************************************************************************************************** 00K0250
SUBROUTINE MAKEJL
CIMENS LC(9),KA(18,2),KQ(9)

PAGE 7
COMMON/KL/KL(1)/KC/KC(1)/KU/KU(1)/KX/KX(1)/NL/NL(1) 00K 0253
CCMNON/N/NN(1)/NP/NP(1)/IJ/IJ(1)/IL/IL(1)/JL/JL(1)/JI/JI(1) 00K 0254
COMMON /M/M/N/N/NER/NER/KAT/KAT/KOF/KOR/KTER/KTER 00K 0255
COMMON /MINE/MINE/LC/LC/KA/KA/IFIN/IFIN/KI/KI/KO/KO/KQ/KQ/K/Q/K 00K 0256
C NUMBERS TO IJ LIST 00K 0257
I=1 00K 0258
DO 1 L=1,N 00K 0259
3 K=NODENO(IJ(2*L-1),IJ(2*L)) 00K 0260
IF(K.LE.M) GO TO 6 00K 0261
IF(M.GE.KQ(5)) GO TO 9 00K 0262
M=M+1 00K 0263
NN(2*M-1)=IJ(2*L-1) 00K 0264
NN(2*M)=IJ(2*L) 00K 0265
IJ(L)=K 00K 0266
NL(I)=N+1 00K 0267
LER=LER+1 00K 0268
19 IF(NL(I+1).GT.L) GO TO 18 00K 0269
I=I+1 00K 0270
IF(I.LT.M) GO TO 19 00K 0271
18 WRITE(KO,90) NN(2*I-1),NN(2*I),NN(2*M-1),NN(2*M) 00K 0272
GO TO 1 00K 0273
6 IJ(L)=K 00K 0274
1 CONTINUE 00K 0275
C FIX IL LIST 00K 0276
C 8 I=1,M 00K 0277
CALL PLACE(NL(I),IL(I)) 00K 0278
8 NL(I)=0 00K 0279
CALL PLACE(N+1,IL(N+1)) 00K 0280
C COUNT J-S 00K 0281
C 10 J=1,N 00K 0282
I=LAST(IJ(J)) 00K 0283
10 NL(I)=NL(I)+1 00K 0284
C FORM JL LIST 00K 0285
KK=1 00K 0286
CALL PLACE(KK,JI(1)) 00K 0287
DO 20 I=1,M 00K 0288
PAGE 8
IF(NL(I).NE.0) GO TO 23
WRITE(KO,91) NN(2*I-1),NN(2*I)
LER=1
23 KK=KK+NL(I)
NL(I)=LDEC(LJ(I))
20 CALL PLACE(KK,JL(I+1))
NL(M+1)=LDEC(JL(M+1))
C START OF JL LIST SEGMENT MOVED TO MAKEJL FRCM TRANSL
C COMPUTE JL LISTS
I=0
LUP=1
DO 22 L=1,N
IF(L.LT.LUP) GO TO 25
L=LACR(IJ(L))
I=NL(K)
J=NL(K)
JI(J)=I
CALL PLACE(L,JI(J))
22 NL(K)=NL(K)+1
END
C END OF JL LIST SEGMENT MOVED TO MAKEJL FRCM TRANSL
100 RETURN
9 LER=100000
WRITE(KO,92)
GO TO 100
90 FORMAT(5+QARC,4A4,18H IS A DEAD END ARC)
91 FORMAT(2HNO ARCC ENDS AT NODE,2A4)
92 FORMAT(27HOTOO MANY NODES IN THIS RUN)
END
C**********************************************************************
SUBROUTINE NODASY
DIMENSION LC(9),KA(18,2),KQ(9)
DIMENSION KE(2),KO(2)
COMMON/KL/KL(1)/KC/KC(1)/KU/KU(1)/KX/KX(1)/NL/NL(1)
COMMON/NN/NN(1)/NP/NP(1)/IJ/IJ(1)/IL/IL(1)/JL/JL(1)/JI/JI(1)
COMMON /M/M/N/N/LER/LER/KAT/KAT/KOR/KOR/KTER/KTER
COMMON /MINE/MINE/LC/LC/KA/KA/IFIN/IFIN/KI/KI/KO/KC/KQ/KQ/K
INTEGER ENC,BLANK
DATA END,BLANK/4HEND ,4H /I=0
3 I=I+1
READ(KOR,90) KD(1),KC(2),KE(1),KE(2),KA(1,1)
IF(KC(1).EQ.END) GO TO 99
IF(KD(1).NE.BLANK) GO TO 2
IF(KE(1).EQ.BLANK) GO TO 3
K=NCDENO(KE(1),KE(2))
IF(K.GT.M) GO TO 6
NP(K)=KA(1,1)
GO TO 3
6 WRITE(KO,91) IKE(1),KE(2)
10 LER=LER+1
GO TO 3
2 WRITE(KG,92) I,KD(1),KC(2),KE(1),KE(2),KA(1,1)
GO TO 10
99 FORMAT(2(A4,A2),8X,Il0)
RETURN
90 FORMAT(2(A4,A2),8X,10)
91 FORMAT(5HOCARD 16,6H NODE A4,A2,12H NOT IN ARCS)
92 FORMAT(37HOCARC PUNCHING ERROR IN NODE CARD NO.I6/1H 2(A4,A2),8X,1)
END
C**********************************************************************************************************************
SUBROUTINE READER
CIMENS COMMON/KL/KL(1)/KC/KC(1)/KU/KU(1)/KX/KX(1)/NL/NL(1)
COMMON/NN/NN(1)/NP/NP(1)/IJ/IJ(1)/IL/IL(1)/JI/JI(1)
COMMON/M/I/A/N/LER/LER/KAT/KAT/KOR/KOR/KTER/KTER/10
COMMON /MINE/MINE/LC/LC/KA/KA/IFIN/IFIN/KI/KI/KO/KC/KQ/KQ/K
INTEGER TAPE1,PUNCH1,NODES1,PRINT
INTEGER ALTER,OUTPUT,CCM#PUT,TAPE,PUNCH,NODES,PRINT
DATA TAPE1,PUNCH1,NODES1,PRINT1/4HAPE ,4HPRINT,4HNODES,4HRNTH/
DATA ALTER,OUTPUT,CCM#PUT/4HALTE,4HOUTP,4HCOMP/
DATA TAPE,PUNCH,NODES,PRINT/4HTAP,4HPUN,4H NCD,4HPRI/
5 READ(KI,95) (KA(I,1),I=1,18)
   IF(KA(1,1).EQ.ALTER) GC TO 18
   IF(KA(1,1).EQ.OUTPUT) GO TO 119
   IF(KA(1,1).EQ.CCMPLT) GO TO 18
   WRITE(KO,96) (KA(I,1),I=1,18)
   GO 15 I=1,18
15 KA(I,2)=KA(I,1)
   GO TO 5
18 WRITE(KO,57)
   WRITE(KO,96) (KA(I,1),I=1,18)
   LER=1
   IF(KA(1,1).EQ.CCMPLT) GO TO 111
20 READ(KI,90) (KA(I,1),I=1,11)
   IF(KA(1,1).EQ.ALTER) GC TO 140
   IF(KA(1,1).EQ.OUTPUT) GO TO 121
   IF(KA(1,1).EQ.CCMPLT) GO TO 111
   GO TO 200
   C COMPUTE
111 WRITE(KO,93) N,M,KQ(4),KQ(5)
999 RETURN
   C SET OUTPUT CONTROL
119 WRITE(KO,96) (KA(I,1),I=1,18)
   L=5
   IF(KA(3,1).EQ.TAPE) L=1
   IF(KA(3,1).EQ.PUNCH) L=2
   IF(KA(3,1).EQ.NODES) L=3
   IF(KA(3,1).EQ.PRINT) L=4
   GO TO 80
121 WRITE(KO,88) (KA(I,1),I=1,6)
120 L=5
   IF(KA(3,1).EQ.TAPE) L=1
   IF(KA(3,1).EQ.PUNCH) L=2
   IF(KA(3,1).EQ.NODES) L=3
   IF(KA(3,1).EQ.PRINT) L=4
80 IF(L=4) 81,86,200
81 LC(L)=1
GO TO 20
86  KQ(7)=1
  GO TO 20

C ALTER
140  IF(KA(7,1).GT.0) GO TO 142
   KA(7,1)=1
142  WRITE(KO,91) (KA(I,1),I=1,11)
    N1=NCENCI(KA(3,1),KA(4,1))
    N2=NCEND0(KA(5,1),KA(6,1))
    IF(N1.GT.M) GO TO 144
   IF(N2.LE.M) GO TO 145
144  WRITE(KO,92)
     LER=1
     GO TO 20
145  LL=LDECR(IL(N1))
     L2=LDECR(IL(N1+1))
     IF(L2.LT.L1) GO TO 144
   GO 147  LL=L1,L2
   IF(LADDR(IJ(LL)).NE.N2) GO TO 147
   KA(7,1)=KA(7,1)-1
   IF(KA(7,1).EQ.0) GO TO 149
147  CONTINUE
    GO TO 144
149  KC(LL)=KA(8,1)
    KU(LL)=KA(9,1)
    KL(LL)=KA(10,1)
    KX(LL)=KX(LL)+KA(11,1)
    GO TO 20

C CARD PUNCHING ERROR
200  LER=1
   WRITE(KO,87) (KA(I,1),I=1,6)
   GO TO 20
87  FORMAT(23H ILLEGAL CCNTRCL CARD (3(A4, A2),1H))
88  FORMAT(1H03(A4, A2))
90  FORMAT(3(A4, A2), I2,4I10)
91  FORMAT(1H0,3(A4, A2),I2,4I10)
92 FORMAT(47H'O THE ARC ON THE ABOVE ALTER CARD IS NOT IN CORE')  OKF03930  00K 0433
93 FORMAT(12H'MO) OF ARCS=I5,2X,13H NO. OF NODES=',15,6X,'(MAXIMUMS FOR  OKF03940  00K 0434
  THIS VERSION : ',15, 'ARCS AND ',15, ' NODES')')  OKF03950  00K 0435
95 FORMAT(18A4)  OKF03950  00K 0436
96 FORMAT(1H018A4)  OKF03960  00K 0437
97 FORMAT(47H'O OUTPUT CCNTRCL CARD MISSING OR OUT OF SEQUENCE)  OKF03970  00K 0438
END  OKF03980  00K 0439

C*******************************************************************************************************
SUBROUTINE TRANSL
DIMENSION LC(9),KA(18,2),KQ(9)
COMMON/KL/KL(1)/KC/KC(1)/KU/KU(1)/KX/KX(1)/NL/NL(1)
COMMON/NN/NN(1)/NP/NP(1)/IJ/IJ(1)/IL/IL(1)/JL/JL(1)/JI/JI(1)
COMMON /M/M/N/N/LER/LER/KAT/KAT/KOR/KOR/KTER/KTER
COMMON /MINL/MINE/LC/LC/KA/KA/IFIN/ IFIN/KI/KI/KO/KO/KQ/KQ/KK
CLEAR NL STORAGE
CALL ERASE(NLM)
C CIRCULATION AND C-3AR
I=0
LUP=1
DO 2 L=1,N
IF(L.LT.LUP) GO TO 13
I=I+1
LUP=LECR(IL(I+1))
13 LU=LADDR(IJ(L))
NL(I)=NL(I)-KX(L)
NL(LU)=NL(LU)+KX(L)
2 KC(L)=KC(L)+NP(I)-NP(LU)
C CIRCULATION MESSAGE FOR NON-ZERO CIRCULATION AND MOVE JL LIST
C CLEAR NL STORAGE
DO 5 I=1,M
IF(NL(I).EQ.0) GO TO 5
WRITE(KO,93) NN(2*I-1),NN(2*I),NL(I)
NL(I)=0
5 CONTINUE
C COMPUTE EXCESS OF X AND UPPER BOUND OVER LOWER BOUND
DO 1 J=1,N
KU(J)=KU(J)-KL(J)

IF(KU(J).GE.0) GO TO 1

WRITE(KO,51) J

LER=LER+1

1 KX(J)=KX(J)-KL(J)

RETURN

JL LIST SEGMENT MOVED FROM TRANSL TO MAKEJL

51 FORMAT(4H0ARC,16,42H HAS LOWER BOUND GREATER THAN UPPER BOUND.)

90 FORMAT(6HONODE 2A4,28H NON-CONSERVATIVE, NET FLOW=II2)

END

SUBROUTINE KILTER(I)

DIMENSION LC(9),KA(18,2),KQ(9)

COMMON/KL/KL(1)/KC/KC(1)/KU/KU(1)/KX/KX(1)/NL/NL(1)

COMMON/NN/NN(1)/NP/NP(1)/IJ/IJ(1)/IL/IL(1)/JI/JI(1)

COMMON/M/N/M/LER/LER/KAT/KAT/KGR/KOR/KTER/KTER

COMMON/MINE/MINE/LC/LC/KA/KA/IFIN/IFIN/KI/KI/KQ/KQ/KQ/KQ

IF(LDECR(IJ(1)).EQ.1) GO TO 70

CALL PLACE(0,IJ(1))

CALL ERASE(NLM)

70 LER=0

5 IF(KC(K)) 10,20,30

10 IF(KX(K).LT.0) GO TO 13

MINE=-KX(K)+KU(K)

GO TO 50

13 MINE=KX(K)-KU(K)

GO TO 60

20 IF(KX(K).LT.0) GO TO 13

IF(KX(K).LT.0) 40,40,35

30 MINE=-KX(K)

GO TO 50

35 MINE=KX(K)

GO TO 60

50 KOR=LADDR(IJ(K))

KAT=C
KTER=I
GO TO 65
60 KOR=I
KAT=1J
KTER=LADDR(IJ(K))
65 CALL LABELN(KBR)
   IF(KBR.EQ.0) GO TO 68
   CALL BREAKT
   GO TO 5
68 CALL UPNOPR
   IF(LER.EQ.0) GO TO 5
40 RETURN
END

C**************************************************************************
SUBROUTINE OUTPUT(KZ)
C
DIMENSION LC(9),KA(18,2),KQ(9)
COMMON/KL/KL(1)/KC/KC(1)/KU/KU(1)/KX/KX(1)/NL/NL(1)
COMMON/NN/NN(1)/NP/NP(1)/IJ/IJ(1)/IL/IL(1)/JL/JL(1)/JI/JI(1)
COMMON/M/N/N/LER/LER/KAT/KAT/KCR/KOR/KTER/KTER
COMMON/MINE/MINE/LC/LC/KA/KA/IFIN/IFIN/KI/KI/KO/KO/KQ/KQ/KQ/KK
DATA KILT,BLANK,IER/1HK,1H,1HN/
INTEGER OUT(9)
LOGICAL CUTTAP,CUTPRT,CUTPCH
DOUBLE PRECISION KCUM
KQ1=KQ(1)
KCUM=0
IF(KZ(101).NE.0) GO TO 10
IF(LER.NE.0) GC TO 30
MZ=KILT
GO TO 100
10 IF(LER.NE.0) GC TO 18
WRITE(KC,99) KZ(101)
18 KZ(101)=MIN0(KZ(101),100)
30 MZ=BLANK
100 K2=KQ(2)
IF(LC(2).EQ.0) GO TO 12
WRITE(KQ1,90) (KA(I,2),I=1,18)
WRITE(K0,89)
12 IF(LC(1).EQ.0) GO TO 41
IF(KQ(6).NE.0) GO TO 24
KQ(6)=1
REWIND K2
24 WRITE(K2,90) (KA(I,2),I=1,18)
WRITE(K0,88)
41 IF(KQ(7).EQ.0) WRITE(KO,91)
GO TO 12
KA(1,2),I=1,18)
GO TO 41
GO TO 24
KA(I,2),I=1,18)

L=1
LL=1
CUTTAP=LC(1).NE.0
CUTPRT=KQ(7).NE.0
CUTPCH=LC(2).NE.0
DO 3 I=1,M
LUP=LDECRI(I(I+1))
302 IF(L.GE.LUP) GO TO 3
LU=LADDR(IJ(L))
LLC=KC(L)
KC(L)=KC(L)-NP(I)+NP(LU)
NX(L)=KX(L)+KL(L)
KU(L)=KU(L)+KL(L)
LZ=KX(L)*KC(L)
KCUM=KCUM+LZ
MX=MZ
II=I+1
LU2=LU+LL
CUT(1)=NN(I-1)
CUT(2)=NN(I)
CUT(3)=NN(LU2-1)
CUT(4)=NN(LU2)
CUT(5)=KC(L)
CUT(6)=KU(L)
CUT(7)=KL(L)
CUT(8)=KX(L)
CUT(9)=LZ
IF(KZ(101).LE.0) GO TO 16
IF(KZ(LL).NE.L) GO TO 16
KZ(101)=KZ(101)-1
LL=LL+1
MX=IEN
16 IF(OLTAP) WRITE(K2,93) CUT, MX
    IF(CUTPRT) WRITE(KC,94) CUT,NP(I),NP(LU),LLC,MX
    IF(CUTPCH) WRITE(KQ1,93) OUT
333 L=L+1
GO TO 302
3 CONTINUE
IF(LC(3).EQ.0) GO TO 15
IF(LC(1)+LC(2).EQ.J) GO TO 27
IF(LC(1).EQ.0) GO TO 203
WRITE(K2,96)
203 IF(LC(2).EQ.0) GO TO 115
WRITE(KQ1,96)
115 GO 200 I=1,M
    IF(LC(1).EQ.0) GO TO E5
    WRITE(K2,95) NN(2*I-1),NN(2*I),NP(I)
85 IF(LC(2).EQ.0) GO TO 200
    WRITE(KQ1,95) NN(2*I-1),NN(2*I),NP(I)
200 CONTINUE
15 IF(LC(1).EQ.0) GO TO 27
    WRITE(K2,97)
27 IF(KQ(7).EQ.0) GO TO 57
    WRITE(KO,98)
    WRITE(KO,999) KCUM
57 IF(LC(2).EQ.0) GO TO 77
    WRITE(KQ1,97)
77 WRITE(KO,92) (LC(I),I=5,M)
RETURN
88 FORMAT(24HOTHIS RUN OUTPUT TO TAPE )
89 FORMAT(25HOTHIS RUN OLTPUT TO PUNCH)
90 FORMAT (18A4/4HARCS22X, 4HCOST5X, 5HUPPER5X, 5HLLOWER10X, 1HX8X, 4HFLOW) OKF05840 OK 0613
91 FORMAT (1H118A4/5HARCS16X, 4HCOST6X, 5HUPPER6X, 5HLLOWER10X, 1HX8X, 4HFLOW) OKF05850 OK 0614
1 4HFLOW9X, 3HPI19X, 3HPI28X, 4HCBAR/1X) OKF05860 OK 0615
92 FORMAT (1HONO OF BREAKTHRU S=112, 22H, NO OF NCNBREAKTHRUS=112, 18H, OKF05870 OK 0616
1NO OF CF CHANGES=112, 42H NO OF NODES FROM WHICH LABELING WAS DONE=OKF05880 OK 0617
2112) OKF05890 OK 0618
93 FORMAT (6X, 2(A4, A2), 2X, 4I10, I12, 1X, A1) OKF05900 OK 0619
94 FORMAT (2(1X, A4, A2), 4(I1, I10), 4I12, 1X, A1) OKF05910 OK 0620
95 FORMAT (6X, A4, A2, 6X, I12) OKF05920 OK 0621
96 FORMAT (6HNODES ) OKF05930 OK 0622
97 FORMAT (3HEND) OKF05940 OK 0623
98 FORMAT (4HEND) OKF05950 OK 0624
99 FORMAT (1H0I5, 23H ARCS ARE CUT OF KILTER) OKF05960 OK 0625
999 FORMAT (2SH) TOTAL SYSTEM CONTRIBUTION = F20.0) OKF05980 OK 0626
ENC OKF05980 OK 0627
C***************************************************************
C************ SUBROUTINE CMPTIM(LV,ENT) ***********************
C PRINTS TIME OF INTRA-SUBROUTINE TRANSFERS OR DATE&TIME
C "TIMING" IS AN M.I.T. INTERNAL SUBROUTINE THAT RETURNS THE CPU TIME
C IN HUNDREDTHS OF SECONDS.
C "WHEN" IS AN M.I.T. INTERNAL SUBROUTINE THAT RETURNS THE DATE AND
C TIME IN THE FOLLOWING 5A4 FORMAT: MM/DD/YY HR*MI*SS*FF
C DIMENSION A(5)
C DOUBLE PRECISION LV,ENT
C INTEGER TNOW,TSTART,TREL
C INTEGER WT
C CALL TIMING(TNOW)
C TREL=TNOW-TSTART
C IF (TREL.LT.0) TREL=TREL+8640000
C TI=TREL/100.
C WRITE(WT,10)LV,ENT,TI
C RETURN
C ENTRY STRTIM(WT)
C CALL TIMING(TSTART)
C CALL WHEN(A)
C WRITE(WT,20) A
RETURN
10 FORMAT(/,T103,29('*'),/T103,'* LV. ',A6,T131,'*'/, 
$T103,'* ENT. ',A6,' @',F7.2,' SEC. *',/T103,29('*')/)
20 FORMAT(/T103,29('*')/T103,'* 
$T103,'* 
TIME = ', 3A4,T131,'*/T103,29('*')/)
END

//STEP EXEC ASMC,PARM.C='LCAC,DECK'
//C.SYSIN DD *
ASSEM START 0
ENTRY LABELN,BREAK,UFNCPR,NODENO
SPACE 5 LABELN SAVE (14,12),,*
SUBROUTINE LABELN(KBR)
(R12 IS BASE FOR THIS PROGRAM) Using *,12
BALR 12,0
LA 11,SAVER
ST 13,4(0,11)
ST 11,8(0,13)
L 11,JIAD
S 11,FOUR
(R11 HAS ADDRESS OF 1J-4)
L 10,NLAD
S 10,FOUR
(R10 HAS ADDRESS OF NL-4)
L 13,KCAD
S 13,FOUR
(R13 HAS ADDRESS OF KC-4)
L 14,KXAD
S 14,FOUR
(R14 HAS ADDRESS OF KX-4)
L 15,KUAD
S 15,FOUR
(R15 HAS ADDRESS OF KU-4)
L 1,0(0,1)
SR 2,2
ST 2,0(0,1) KBR=0
ST 1,SAVER
L 1,JIAD
S 1,FOUR
(R1 HAS ADDRESS OF JI-4)
L 2,KORAD
L 2,0(0,2)
ST 2,1 I=KOR

PAGE 19
L 3, 8
L 4, NUP
SR 7, 7
CH 7, 4(0, 11)
BNE L 14
L 7, IFINAD
L 7, 0(C, 7)
STH 7, 2(2, 10)
L 7, 1
STH 7, 4(0, 11)
L 4, EIGHT
L 14
L 9, ILAD
S 9, FOUR
LH 5, 4(2, 9)
BCTR 5, 0
SLL 5, 2
LH 6, 0(2, 9)
SLL 6, 2
L 2 = LDECR(IL(I+1)) - 1
L 16
CR 5, 6
BL L 28
LH 8, 2(6, 11)
SLL 8, 2
SR 7, 7
C 7, 0(8, 10)
BNE L 27
C 7, 0(6, 13)
BL L 21
L 7, 0(6, 14)
C 7, 0(6, 15)
BL L 22
B L 27
L 21
SR 7, 7
C 7, 0(6, 14)
BNH L 27
L 22
L 7, 1
(IF(LDECR(IJ(I)).NE.0) GO TO 14)
NU = 2
(R3 HAS NU*4)
(R4 HAS NUP*4)
IF (LDECR(IJ(1)).NE.0) GO TO 14
NL(I) = IFIN
CALL PLACE(I, IJ(I))
NUP = 2
(R9 HAS ADDRESS OF IL-4)
(L2 = LDECR(IL(I+1)) - 1)
16 IF (L2 * L.T. L) GO TO 28
J = LADDR(IJ(L))
(R8 HAS J*4)
(IF(NL(J).NE.0) GO TO 27)
C 7, 0(6, 13)
(BL L 21)
L 7, 0(6, 14)
C 7, 0(6, 15)
BL L 22
B L 27
L 21
SR 7, 7
C 7, 0(6, 14)
BNH L 27
L 22
L 7, 1
(IF(KC(L).GT.0) GO TO 21)
(IF(KX(L) - KU(L)) 22, 27, 27
21 IF (KX(L).GE.0) GO TO 27
0KF06220 0OK 0717
0KF06650 0OK 0720
0KF06630 0OK 0718
0KF06640 0OK 0719
0KF06650 0OK 0720
0KF06660 0OK 0715
0KF06650 0OK 0714
0KF06590 0OK 0714
0KF06580 0OK 0713
0KF06570 0OK 0712
0KF06560 0OK 0711
0KF06550 0OK 0710
0KF06540 0OK 0709
0KF06530 0OK 0708
0KF06520 0OK 0707
0KF06510 0OK 0706
0KF06500 0OK 0705
0KF06400 0OK 0703
0KF06370 0OK 0692
0KF06360 0OK 0691
0KF06360 0OK 0690
0KF06350 0OK 0689
0KF06340 0OK 0689
0KF06330 0OK 0688
0KF06320 0OK 0687
0KF06310 0OK 0686
0KF06300 0OK 0685

ST 7,0(8,10) 22 NL(J)=I OKF06660 00K 0721
SRL 6,2 OKF06670 00K 0722
STH 6,0(8,10) CALL PLACE(L,NL(J)) OKF06680 00K 0723
SLL 6,2 OKF06690 00K 0724
SRL 8,2 OKF06700 00K 0725
STH 8,0(4,11) CALL PLACE(J,IJ(NUP)) OKF06710 00K 0726
A 4,F0UR OKF06720 00K 0727
L 7,KTERAC OKF06730 00K 0728
L 7,0(0,7) OKF06740 00K 0729
CR 7,8 IF(J.EQ.KTER) GO TO 47 OKF06750 00K 0730
BE L47 OKF06760 00K 0731
L27 A 6,F0UR 27 L=L+1 OKF06770 00K 0732
B L16 GO TO 16 OKF06780 00K 0733
L28 L 9,JLAD OKF06790 00K 0734
S 9,F0UR OKF06800 00K 0735
LH 5,4(2,9) (R9 HAS ADDRESS OF JL-4) OKF06810 00K 0736
BCTR 5,0 OKF06820 00K 0737
SLL 5,2 OKF06830 00K 0738
LH 6,3(2,9) L=LDECR(JL(I)) OKF06840 00K 0739
SLL 6,2 OKF06850 00K 0740
L30 CR 5,6 30 IF(L.LT.L) GO TO 43 OKF06860 00K 0741
BL L43 OKF06870 00K 0742
LH 8,2(6,1) J=LADDR(JI(L)) OKF06880 00K 0743
SLL 8,2 OKF06890 00K 0744
SR 7,7 OKF06900 00K 0745
C 7,0(8,10) IF(NL(J).NE.0) GO TO 42 OKF06910 00K 0746
BNE L42 OKF06920 00K 0747
LH 9,0(6,1) KR=LDECR(JI(L)) OKF06930 00K 0748
SLL 9,2 (R9 HAS KR*4) OKF06940 00K 0749
C 7,0(9,13) IF(KC(KR).GE.0) GO TO 36 OKF06950 00K 0750
BNE L36 OKF06960 00K 0751
L 7,0(9,14) OKF06970 00K 0752
C 7,0(9,15) OKF06980 00K 0753
BH L37 IF(KX(KR)-KU(KR)) 42,42,37 OKF06990 00K 0754
B L42 OKF07000 00K 0755
L36 SR 7,7 OKF07010 00K 0756

PAGE 21
C 7,0(9,14) 36 IF(KX(KR),LE.0) GO TO 42
BNL L42
L37
L 7,1
LCR 7,7
ST 7,0(8,10)
SRL 9,2
SRL 9,0(8,10)
STH 8,2
STH 8,0(4,11)
A 4,FOUR
L 7,KTERAD
L 7,0(0,7)
CR 7,8
BE L47
L 42
A 6,FOUR
B L30
L43
CR 3,4
BNL L48
LH 2,0(3,11)
A 3,FOUR
ST 2,1
SLL 2,2
B L14
L47
L 1,SAVER
L 7,CNE
ST 7,0(0,1)
L48
SRL 3,2
BCTR 3,0
L 7,LCAD
A 3,28(0,7)
ST 3,28(0,7)
ST 4,NUP
L 13,SAVER+4
RETURN
EJECT
BREAKT SAVE (14,12),*, *

SUBROUTINE BREAKT

OKF07020 00K 0757
OKF07030 00K 0758
OKF07040 00K 0759
OKF07050 00K 0760
OKF07060 00K 0761
OKF07070 00K 0762
OKF07080 00K 0763
OKF07090 00K 0764
OKF07100 00K 0765
OKF07110 00K 0766
OKF07120 00K 0767
OKF07130 00K 0768
OKF07140 00K 0769
OKF07150 00K 0770
OKF07160 00K 0771
OKF07170 00K 0772
OKF07180 00K 0773
OKF07190 00K 0774
OKF07200 00K 0775
OKF07210 00K 0776
OKF07220 00K 0777
OKF07230 00K 0778
OKF07240 00K 0779
OKF07250 00K 0780
OKF07260 00K 0781
OKF07270 00K 0782
OKF07280 00K 0783
OKF07290 00K 0784
OKF07300 00K 0785
OKF07310 00K 0786
OKF07320 00K 0787
OKF07330 00K 0788
OKF07340 00K 0789
OKF07350 00K 0790
OKF07360 00K 0791
OKF07370 00K 0792

PAGE 22
BALR 12, J
USING *, 12
LA 11, SAEVR
ST 13, 4(0, 11)
ST 11, 8(0, 13)
L 16, NLAD
S 10, FOUR
L 11, IJAD
S 11, FOUR
L 13, KCAD
S 13, FOUR
L 14, KXAD
S 14, FOUR
L 15, KUAD
S 15, FOUR
L 8, MINEAD
L 8, 0(0, 8)
L 7, LCAC
L 9, 16(0, 7)
A 9, ONE
ST 9, 16(0, 7)
L 1, LERAD
SR 7, 7
ST 7, 3(0, 1)
L 4, KTERAD
L 4, 0(0, 4)
SLL 4, 2
L 2, FOUR
LR 1, 2
L 3, MAD
L 3, 0(0, 3)
DO 29 J = 1, M
SLL 3, 2
LH 5, 2(4, 10)
LH 6, 2(4, 10)
SLL 6, 2
L 7, IFINAD

(R12 IS BASE FOR THIS PROGRAM)
(R10 HAS ADDRESS OF NL-4)
(R11 HAS ADDRESS OF IJ-4)
(R13 HAS ADDRESS OF KC-4)
(R14 HAS ADDRESS OF KX-4)
(R15 HAS ADDRESS OF KU-4)

LC(5) = LC(5) + 1
LER = 0
KT = KTER
KP = LADDR(NL(KT))
KK = LDECR(NL(KT))
(R5 HAS KP)
(R6 HAS KK*4)
LH  7,2(0,7)
CR  5,7
BE  B31
LTR 5,5
BP  B23
SR  7,7
C  7,0(6,13)
BNH B19
L  7,0(6,14)
S  7,0(6,15)
CR  8,7
BNH B21
LR  8,7
B  B21
B19 L  7,0(6,14)
CR  8,7
BNH B21
LR  8,7
B21 SRL 6,2
LCR 6,6
STH 6,0(1,11)
B  B29
B23 SR  7,7
C  7,0(6,13)
BL  B26
L  7,0(6,15)
S  7,0(6,15)
CR  8,7
BNH B28
LR  8,7
B  B28
B26 S  7,0(6,14)
CR  8,7
BNH B28
LR  8,7
B28 SRL 6,2

IF(KP.EQ.IFIN) GC

TO 31

IF(KP.GT.0) GO TO 23

IF(KC(KK).GE.0) GO TO 19

MINE=MINO(MINE,KX(KK)-KU(KK))

GO TO 21

19 MINE=MINO(MINE,KX(KK))

21 KK=-KK

CALL PLACE(KK,IJ(J))

GO TO 29

23 IF(KC(KK).GT.0) GO TO 26

MINE=MINO(MINE,KU(KK)-KX(KK))

GO TO 28

26 MINE=MINO(MINE,-KX(KK))
829

TH

LPR

SLL

BXLE

L

L

SLL

L

L

S

BP

AR

ST

B

SR

ST

S

LR

SRL

L

L

AR

A

ST

LR

SR

AH

BP

LCR

SLL

L

SR

ST

B

SLL

28 CALL PLACE(KK,IJ(J))

29 KT=IABS(KP)

(R9 HAS K*4)

(R5 HAS KAT)

31 IF(KAT.GT.4) GO TO 34

KX(K)=KX(K)+MINE

GO TO 35

KX(K)=KX(K)-MINE

(R3 HAS JJ*4)

JJ=J-1

DO 43 J=1,JJ

43

ST

B

SR

ST

S

LR

SRL

L

L

AR

A

ST

LR

SR

AH

BP

LCR

SLL

L

SR

ST

B

SLL

OKF08100 00K 0865

OKF08110 00K 0866

OKF08120 00K 0867

OKF08130 00K 0868

OKF08140 00K 0869

OKF08150 00K 0870

OKF08160 00K 0871

OKF08170 00K 0872

OKF08180 00K 0873

OKF08190 00K 0874

OKF08200 00K 0875

OKF08210 00K 0876

OKF08220 00K 0877

OKF08230 00K 0878

OKF08240 00K 0879

OKF08250 00K 0880

OKF08260 00K 0881

OKF08270 00K 0882

OKF08280 00K 0883

OKF08290 00K 0884

OKF08300 00K 0885

OKF08310 00K 0886

OKF08320 00K 0887

OKF08330 00K 0888

OKF08340 00K 0889

OKF08350 00K 0890

OKF08360 00K 0891

OKF08370 00K 0892

OKF08380 00K 0893

OKF08390 00K 0894

OKF08400 00K 0895

OKF08410 00K 0896

OKF08420 00K 0897

OKF08430 00K 0898

OKF08440 00K 0899

OKF08450 00K 0900

PAGE 25
L 7,0(6,14)
AR 7,8
ST 7,0(6,14)
BXLE 1,2,B36
LR 1,2
L 3,MAD
L 3,0(0,3)
SLL 3,2
SR 7,7

BXLE 1,2,B44
ST 7,3(1,10)
SLL 7,4(0,11)
L 13,SAVER+4
RETURN (14,12),T
EJECT

UPNOPR
SAVE (14,12),*
BALR 12,0
USING *,12
LA 11,SAVER
ST 13,4(0,11)
ST 11,8(0,13)
L 9,ILAD
S 9,FOUR
L 11,IJAD
S 11,FOUR
L 10,NLAD
S 10,FOUR
L 14,KXAD
S 14,FOUR
L 15,KUAD
S 15,FOUR
L 13,KCAD
S 13,FOUR
L 7,LCAD
L 6,20(0,7)
A 6,ONE

42 KX(KK)=KX(KK)+MINE
43 CONTINUE
45 NL(J)=0

CALL PLACE(C,IJ(1))
RETURN

SUBROUTINE UPNOPR
(R12 IS BASE FOR THIS PROGRAM)
(R9 HAS ADDRESS OF IL-4)
(R11 HAS ADDRESS OF IJ-4)
(R10 HAS ADDRESS OF NL-4)
(R14 HAS ADDRESS OF KX-4)
(R15 HAS ADDRESS OF KU-4)
(R13 HAS ADDRESS OF KC-4)
LC(6)=LC(6)+1

PAGE 26
ST  6,20(0,7)
L  8,IF INAD
L  8,0(0,8)
SR  4,4
SR  5,5
L  2,FOUR
LR  1,2
L  3,NAD
L  3,(0,3)
SLL  3,2
U12  CR  1,5
      BNH  U16
A  4,FOUR
LH  5,4(4,9)
BCTR  5,0
SLL  5,2
      U16  LH  6,2(1,11)
SLL  6,2
SR  7,7
C  7,0(4,10)
BE  U20
C  7,0(6,10)
BNE  U24
L  7,0(1,14)
C  7,0(1,15)
BL  U22
B  U24
      U20  C  7,0(6,10)
      BE  U24
      C  7,0(1,14)
      BAL  U24
      U22  L  7,0(1,13)
LPR  7,7
CR  8,7
      BNH  U24
      LR  8,7

(R8 HAS NDELTA)
NDELTA=IF IN
I=0
KUP=0
(R4 HAS I*4)
(R5 HAS KUP*4)
(R3 HAS N*4)
DO 24 L=1,N
(R2 HAS 4)
(I=1+1)
(R1 HAS L*4)
KUP=LDECR(IL(I)+1)-1
16 J=LADDR(IJ(L))
16 J=LADDR(IJ(L))
16 J=LADDR(IJ(L))

IF (L.LE.KUP) GO TO 16
IF(L.LE.KUP) GO TO 16
IF(L.LE.KUP) GO TO 16

IF(NL(I).EQ.0) GO TO 20
IF(NL(J).NE.0) GO TO 24
IF(NL(J).NE.0) GO TO 24
IF(NL(J).NE.0) GO TO 24

IF(KX(L).LE.0) GO TO 24
IF(KX(L)-KU(L)) 22,24,24
IF(KX(L)-KU(L)) 22,24,24
IF(KX(L)-KU(L)) 22,24,24

20 IF(NL(J).EQ.0) GO TO 24
22 LL=IABS(KC(L))

NDELTA=MINO(LL,NDELTA)
CONTINUE

IF(NDELTA.LT.IF IN) GO TO 31

(R5 HAS K*4)

IF(KX(K).NE.KU(K)) GO TO 51

(R1 HAS I*4)

IF(NL(I).NE.0) GO TO NP(I)

IF(KX(K).EQ.0) GO TO 28

IF(KX(K).NE.KU(K)) GO TO 51

31 DO 47 I=1,M

(L2 HAS L2*4)

L=LDECR(IL(I))

(R5 HAS L*4)

IF(NL(I).NE.0) GO TO 41

(IF(NL(I).NE.0) GO TO 41

NP(I)=NP(I)+NDELTA

IF(NP(I).GT.100000000) GO TO 49

IF(L2.LT.L) GO TO 47
J=LADDR(IJ(L))

IF(NL(J).EQ.0) GO TO 40

KC(L)=KC(L)+NDELTA

J=LADDR(IJ(L))

IF(NL(J).NE.0) GO TO 46

KC(L)=KC(L)-NDELTA

L=L+1

GO TO 41

IF(L2.LT.L) GO TO 47

J=LADDR(IJ(L))

L=L+1

GO TO 41

CONTINUE

GO TO 50

LER=404

GO TO 50

END

FUNCTION NODENO(IN1,IN2)

OKF09540 00K 1009
OKF09550 00K 1010
OKF09560 00K 1011
OKF09570 00K 1012
OKF09580 00K 1013
OKF09590 00K 1014
OKF09600 00K 1015
OKF09610 00K 1016
OKF09620 00K 1017
OKF09630 00K 1018
OKF09640 00K 1019
OKF09650 00K 1020
OKF09660 00K 1021
OKF09670 00K 1022
OKF09680 00K 1023
OKF09690 00K 1024
OKF09700 00K 1025
OKF09710 00K 1026
OKF09720 00K 1027
OKF09730 00K 1028
OKF09740 00K 1029
OKF09750 00K 1030
OKF09760 00K 1031
OKF09770 00K 1032
OKF09780 00K 1033
OKF09790 00K 1034
OKF09800 00K 1035
OKF09810 00K 1036
OKF09820 00K 1037
OKF09830 00K 1038
OKF09840 00K 1039
OKF09850 00K 1040
OKF09860 00K 1041
OKF09870 00K 1042
OKF09880 00K 1043
OKF09890 00K 1044
USING *,12
L
A
11,SAVER
S
10,FOUR
N3
C
7,0(4,10)
N9
A
4,EIGHT
SRL
3,3
A
3,ONE
N12
SRL
1,3
ST
1,20(0,13)
N13
RETURN (14,12),T
SPACE 2
FOUR DC F'1'
EIGHT DC F'8'
ONE DC F'1'
I
DS 1F
NUP DS 1F
SAVER DS 18F

(R12 IS BASE FOR THIS PROGRAM)

(R10 HAS ADDRESS OF NN-4)

(R7 HAS IN1)

(R8 HAS IN2)

(R2 HAS 8)

DO 9 K=1,M

(R3 HAS M*8)

(R1 HAS K*8)

(R4 HAS 4)

BNE N9 IF(IN1.EQ.NN(2*K-1).AND.IN2.EQ.NN(2*K)) GO TO 12

C
8,0(1,10)

BE
N12

A
N10

NODENO=M+1

GO TO 13

N10

12 NODENO=K

ST
1,20(0,13)

13 RETURN

END

PAGE 30
CALL PLACE(A,B)
PLACES THE RIGHTMOST 16 BITS OF A
IN THE LEFTMOST 16 BITS OF B

THE FUNCTION LADDR(A) RETURNS THE
RIGHTMOST 16 BITS OF A AS A 32-BITS FORTRAN INTEGER.

THE FUNCTION LDECR(A) RETURNS THE
LEFTMOST 16 BITS OF A AS A 32-BITS FORTRAN INTEGER

/ *
**********************************************
* ASSEMBLER LANGUAGE SUBROUTINE ERASE *
* 00000003 OOK 1159 *
* 00000010 OOK 1151 *
PAGE 32
* WRITTEN BY JOHN W. KIDSON
* MIT DEPARTMENT OF METEOROLOGY
* TO SET ELEMENTS OF REAL OR INTEGER ARRAYS TO ZERO. A1,A2,...
* ARE ARRAY NAMES AND N1,N2,... ARE INTEGER VALUES OR
* EXPRESSIONS GIVING THE ARRAY SIZES.
* I.E. - CALL ERASE(C,26*31,N,7*31,E,254)
** I.E. - CALL ERASE(C,26*31,N,7*31,E,254)
**
*** *********************************************************

ERASE
SAVE (14,12),,*
EALR 12,0
LSING *,12
SR 0,0
SR 2,2
L 6,=F'4'
E1
L 3,0(2,1)
L 4,4(2,1)
L 7,0(4)
SLA 7,2
SR 7,6
SR 5,5
E2
ST 0,0(5,3)
BXLE 5,6,E2
LTR 4,4
BM RETN
A 2,=F'8'
B E1
RETN
END

PAGE 33
**QKCCRE MAIN PROGRAM**

**QKCCRE VERSION 12-15-72**

REAL*8 RTC

CCMCCN/FXDDAT/MXZONE,MXCYTO,MXRCRS,MXRCRK,MXFULK,IRCNS,IRCNS,IFULK

$NRCRS,NRCRK,NFULK,EFF,XF,XW,TXRATE,PRVATE,TBASE,DTPRE,DTPST,

$ECTY2F6,CCHRAT,FCOR,FFAB,FSAR,FCRE,NCYCIN,NCYCXS,NCYCTO,NZONE,NZP,

$ZONEKG,ECHDOV,EFFAV,MS

CCMCCN/PRINTS/RELCST,INCCST,BALCST,NBLCST,PIDat,PRATCS,RED,WT

LOGICAL RELCST,INCCST,BALCST,NBLCST,PIDat,PRATCS

INTEGER RD,WT

DIMENSION ELAME(50,20),NECBAL(20),TE(20),TS(20),CATITL(20)

DIMENSION ECPLM(20),TO(20)

DATA $NEWB$,CASE$,STOP$/'NEW ',CASE',STOP'/

MXESX2=50

PRINT 900

10 CALL ICNPUT

20 CALL ICNPUT

WRITE(WT,921) CATITL

IF(CATITL(1).EQ.$NEWB$) GO TO 10

IF(CATITL(1).EQ.$STOP$) CALL ICERRS('QKCCRE',8)

IF(CATITL(1).NE.$CASE$) CALL ICERRS('QKCCRE',3)

READ (RD,920) CATITL

WRITE(WT,922) CATITL

READ (RD,923) NCYCIN,NCYCXS,IDNUM,ECHDOV

WRITE(WT,924) NCYCIN,NCYCXS,IDNUM,ECHDOV

NCYCTO=NCYCIN+NCYCXS

CALL ERAE(ELAME,MXESX2,MCYTO,TS,MCYTO,TE,MCYTO,NECBAL,MCYTO)

NXNES=0

CD 30 IDUM=1,NCYCTO

PAGE 1
**Definitions of Important Variables**

- **ACCYC**: Average Cycle Cost at It's Mid-Point ($/MWHE)
- **ACEOCD**: Average Cost of Batch Discharge at End of Cycle ($/MWHE)
- **BUPN**: Burnup (MWd/kg)
- **BALCST**: Print Detailed Cost Tables for Balanced EC's?
- **EASETM**: Base Time for Present Valuing (Years)
- **BACST**: Total Batch Cost (10^3 $)
- **BSRT**: Zone Burnups of Fuels at Start of Simulation (MWd/kg)
- **C**: Unit Batch Cost ($/kg)
- **CCRATE**: Carrying Charge Rate (Fraction)
- **CECRIT**: First Cycle Energy Available Before Barely Critical (GWHE)
- **CESTCH**: Upper Limit on Stretchout Energy (GWHE)
- **CTC**: On-Line Cycle Length (Years)
- **CTPRE**: Effective Delay Time for Pre-Reactor Payments (Years)
- **DTPST**: Effective Delay Time for Post-Reactor Receipts (Years)
- **CTY2F6**: Effective Delay Time from Yellowcake to UF6 (Years)
- **EC**: Electrical Energy Produced in the Cycle (GWHE)
- **ECHDOV**: GWHE Held Over for Prod. Beyond Horizon in Split Cycle (GWHE)
- **ECUPLM**: Upper Limit on Cycle Production (GWHE)
- **EFF**: Effinc
C E F F A V = E F F N E T
C E F F I N C = R E A C T O R I N C R E M E N T A L E F F I C I E N C Y (FRACTION)
C E F F N E T = R E A C T O R N E T T H E R M A L E F F I C I E N C Y (FRACTION)
C E L A M E = S A N D W I C H E C M A T R I X O F E C ' S , L A M B D A S A N D E C ' S (G W H E , $ / M W H E )
C E P F F X = F I X E D E N R I C H M E N T S O F I N I T I A L C Y C L E S ( W / O U - 2 3 5 )
C E R R C O D = A C C U M U L A T E D E R R O R C O D E
C F C C R = Y I E L D I N C C O N V E R S I O N S T E P O F F U E L C Y C L E (FRACTION)
C F C R E = Y I E L D I N R E C Y C L E C O N V E R S I O N S T E P O F F U E L C Y C L E (FRACTION)
C F F A B = Y I E L D I N F A B R I C A T I O N S T E P O F F U E L C Y C L E (FRACTION)
C F U L C O N = S E T S O F E M P I R I C A L F U E L C O N S T A N T S
C I F U L K = F U E L C O N S T A N T S I N D E X
C I F U L K A = P O I N T E R T O S E T O F F U E L C O N S T A N T S T O B E S I M U L A T E D
C I N C C S T = P R I N T I N C R E M E N T A L C O S T T A B L E ?
C I R C R K = R E A C T O R C O N S T A N T S I N D E X
C I R C R S = R E A C T O R I N D E X
C M O D I R R = M O D E O F I R R A D I A T I O N
C M W C A P = R E A C T O R R A T E D C A P A C I T Y (M W E)
C M X C Y T 0 = M A X I M U M A L L O W E D V A L U E O F N C Y C T O
C M X F U L K = M A X I M U M N U M B E R O F A L L O W A B L E S E T S O F F U E L C O N S T A N T S
C M X R C R K = M A X I M U M N U M B E R O F A L L O W A B L E S E T S O F R E A C T O R C O N S T A N T S
C M X Z C N E = M A X I M U M N U M B E R O F Z C N E S
C N A M E = R E A C T O R N A M E
C N B L C S T = P R I N T D E T A I L E D C O S T T A B L E F O R U N B A L A N C E D E C ' S ?
C N C Y C I N = N U M B E R O F C Y C L E S I N V O L V E D I N HORIZON
C N C Y C T O = T O T A L N U M B E R O F C Y C L E S = N C Y C I N + N C Y C X S
C N C Y C X S = N U M B E R O F E X C E S S C Y C L E S B E Y O N D HORIZON

PAGE 4
NECBAL = POSITION OF ECBAL WITHIN A COLUMN OF EC'S OF ELAME
NFULK = NUMBER OF SETS OF FUEL CONSTANTS READ IN
NOESX2 = (NUMBER OF EC'S)*2 IN EACH CYCLE OF THE SIMULATION
NOZONE = NUMBER OF ZONES IN FUEL MANAGEMENT SCHEME
ARCRK = NUMBER OF SETS OF REACTOR CONSTANTS READ IN
NRCRS = NUMBER OF SETS OF REACTOR SPECS. READ IN
AZONE = NOZONE
AZF = NOZNE + 1
PBATCS = PRINT DETAILED COST FOR ALL BATCHES?
FIREAT = PRINT DATA FOR EACH IRRADIATION CYCLE?
FOWFRC = ZONE POWER-SHARING FRACTIONS OF STARTING CYCLE
PVFACT = PRESENT VALUE OF 1$ AT MID-PT. CF CYCLE
PVRAT = PRESENT VALUE RATE (FRACTION PER YEAR)
PVRATE = PVRAT
PVRTC = PRESENT VALUE OF REACTOR TOTAL COST (10**3 $)
PVTNCYC = PRESENT VALUE OF CYCLE COST (10**3 $)
RCRC = SETS OF EMPIRICAL REACTOR CONSTANTS
RD = UNIT NUMBER OF COMPUTER INPUT READING DEVICE
RELCS = PRINT RELATIVE COST TABLE?
SRCINV = UN-DEPREC. SRC. INVENTORY OF STARTING FUELS ($/KG-FAB)
TBASE = BASE TIME FCP PRESENT VALUING (YEARS)
TCCYC = TOTAL CYCLE COST AT IT'S MID-PT. (10**3 $)
TCEOCD = TOTAL COST OF BATCH DISCHARGED AT END OF CYCLE (10**3 $)
TE = ENDING CYCLE DATES (YEARS)
TMID = MID-POINT OF CYCLE (YEARS)
TO = CYCLE OPERATING TIME (YEARS)
TREFUL = REFUELING DATE (YEARS)
TS = STARTING CYCLE DATES (YEARS)
TXRATE = INCOME TAX RATE (FRACTION)
LNTCOR = UNIT CONVERSION COST ($/KG-U CONV)
LNTCRE = UNIT RECYCLE CONVERSION COST ($/KG-U CONV)
LNTFAB = UNIT FABRICATION COST ($/KG-FAB)
LNTPUV = UNIT PLUTONIUM VALUE ($/GM-FIS.PU)
LNTSAR = UNIT SHIP.&REPRCC. COST ($/KG-SAR)
LNTSWU = UNIT SEPARATIVE WORK COST ($/KG-SWU)
LNTYEL = UNIT YELLOWCAKE COST ($/LB-U308)
C  WT  =  UNIT  NUMBER  OF  COMPUTER  OUTPUT  WRITING  DEVICE
C  XF  =  ENRICHMENT  OF  YELLOWCAKE  (WT.FR.  U-235)
C  XW  =  ENRICHMENT  OF  DIFFUSION  PLANT  TAILS  (WT.FR.  U-235)
C  ZEROTH =  TOTAL  HEAT  REQT.  FOR  ZERO  POWER  DURING  TO  (GWHTH)
C  ZONEKG = ZONKG
C  ZONKG = MASS  RELOADED  AT  EACH  REFUELING  (KILOGRAMS)
C******************************************************************************
C END  OF  DEFINITIONS******************************************************************************

REAL*8  PVRTC
DIMENSION  G(1000)
DIMENSION  TS(NCYCTO),TE(NCYCTO),NECBAL(NCYCTO),TO(NCYCTO),
$ELAME(MXESX2,NCYCTO),ECUPLM(NCYCTO)
$COMMCA/ARDATA/IDNO(15),NAME(15),MWCAP(15),EFFNET(15),IRCRA(15),
$IFULKA(15),NOZONE(15),ZONKG(15),DECRIT(15),DESTCH(15),NCYCFCX(15),
$EPFFX(20,15),EPFSRT(10,15),BSRT(10,15),FABINV(10,15),SRCINV(10,15),
$POWFRC(10,15),RCRCCN(18,15),FULCON(48,5),EFFINC(15)
DIMENSION  NOESX2(20)
COMMON/FXDDAT/MXZONEMXCYTCMXRCRSMXRCRKMXFULK,
$NRCRS,IRCRA,NCRK,NFULK,EFF,XF,XW,TXRATE,PVRATE,TBASE,DTPRE,DTPST,
$TY2F6,CCRATE,FCOR,FFAB,FSAR,FCRE,DUMMY1,DUMMY2,DUMMY3,NZONE,NZP,
$ZONEKG,DUMMY4,EFFAV,MKS
COMMON/PRINTS/RELCST,INCCST,NLCST,NBLCST,PIRDAT,BATCS,DT,WT
INTEGER  RD,WT
INTEGER  DUMMY1,DUMMY2,DUMMY3
DUMMY1=NCYC
DUMMY2=NCYCS
DUMMY3=NCYCTO
DUMMY4=ECHDCV
GO TO 5
C
C  ENTRY  ICNPUT
C  ENTRY  POINT  TO  INCORE  AS  SIGNAL  TO  PREPARE  FOR  SIMULATION  BY
C  READING  PERTINENT  INPUT  CARDS
C
C SET  VERSION  MAXIMUMS

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C

5 IF(NCYCIN+NCYCXS.NE.NCYCTO) CALL ICERRS('INCORE',6)
NCYCTO=NCYCIN+NCYCXS
IF(NCYCTO.GT.MXCYTO) CALL ICERRS('INCORE',5)
PVRAT=PVRATE
BASETM=TBASE
DO 10 I=1,NPCRS
   IF(IDNO(I).EQ.IDNUM) GO TO 20
  10 CONTINUE
   CALL ICERRS('INCORE',7)

20 IRCRS=1
NZONE=NOZONE(IRCRS)
NZP=NZONE+1
ZONEKG=ZCNKG(IRCRS)
IRCRK=IRCRA(IRCRS)
IFULK=IFLLKA(IRCRS)
EFF=EFFINC(IRCRS)
EFFAV=EFFNET(IRCRS)
MWS=MWCAP(IRCRS)
EGRIT1=DECRCR1(IRCRS)
STCHLM=DESTCM(IRCRS)
C
SETUP POINTERS AND INITIALIZE SOME SUBROUTINES
NCYCTP=NCYCTO+1
LTREFU=1
LTMID =LTREFU+NCYCTP
LDTC = LTMID +NCYCTP
LMODIR = LTC +NCYCTP
LUNTYE = LMODIR +NCYCTP
LUNTCO = LUNTYE +NCYCTP
LUNTSW = LNTCC +NCYCTP
LUNTFA = LUNTSW +NCYCTP
LUNTRA = LUNTFA +NCYCTP
LUNTCR = LUNTRA +NCYCTP
LUNTPU = LUNTCR +NCYCTP
LPVFAC = LUNTPU +NCYCTP
LEC = LPVFAC +NCYCTP
LPVTCC = LEC +NCYCTP
LTCCYC = LPVTCC +NCYCTP*2
LACCYC = L TCCYC +NCYCTP*2
LTCEOC = LACCYC +NCYCTP
LACEOC = LTCEOC +NCYCTP
LZEROH = LACEOC +NCYCTP
LEPF = LZEROH +NCYCTP
LB = LEPF +NZP*NCYCTP
LBATCS = LB +NZP*NCYCTP
LA = LBATCS +NZP*NCYCTP
LBC = LA +NZP
LCBC = LBC +NZP
LDT = LDBC +NZP
LKGU = LDT +NZP
LEPNOW = LKGU +NZP
LUVALU = LEPNOW +NZP
LGMP = LUVALU +NZP
LIUF6 = LGMP +NZP
LIFAB = LIUF6 +NZP
LISRCC = LIFAB +NZP
LIPUV = LISRCC +NZP
LITOT = LIPUV +NZP
LTCCST = LITOT +NZP
LACST = LTCCST +NZP
LNEXT = LACST +NZP
LAST=LNEXT-1
LAST=21*NCYCT+3*NZP*NCYCT+15*NZP
IF(LAST.GT.MXLAST) WRITE(WT,9J0) LAST,MXLAST
IF(LAST.GT.MXLAST) CALL ICERRS('INCORE',4)
DUMMY=EMPRCL(FULCCN(1,IFULK),RCRCON(1,IRCRK))
CALL INIT3(FABINV(1,IRCRS),SRCINV(1,IRCRS),
\$G(LEPF),G(LDTC),G(LB),G(LUNTYE),G(LUNCTO),G(LUNTSW),
\$G(LUNTF),G(LUNTSA),G(LUNCTCR),G(LUNTPU),G(LTCECC),G(LACEOC),
\$G(LA),G(LBC),G(LDBC),G(LDT),G(LKGU),G(LPNCW),
\$G(LUVALU),G(LGMF),G(LIFU6),G(LIFAB),G(LISRCA),G(LIPUV),
\$G(LITOT),G(LTCS),G(LACST))
MX2EUS=0
DO 45 N=1,NCYCT1
DO 30 I=1,MXESX2,2
IF(ELAME(I,N).EQ.0.0) GO TO 40
CONTINUE
I=MXESX2/2*2+1
40 NOESX2(N)=I-1
45 MX2EUS=MAX0(MX2EUS,NOESX2(N))
CALL FULSIM(MXESX2,NOESX2,ELAME,NECBAL,EPFSRT(1,IRCRS),
\$EPFX1(1,IRCRS),BSRT(1,IRCRS),POFWRC(1,IRCRS),TS,TE,
\$G(LDTC),G(LMCDIR),G(LUNTYE),G(LUNCTO),G(LUNTSW),G(LUNTF),
\$G(LUNTSA),G(LUNCTCR),G(LUNTPU),G(LPVFAC),C(LEC),G(LPVCY),
\$G(LTCCYC),G(LACCYC),G(LTCEOC),G(LACEOC),G(LEPF),G(LB),
\$G(LBATS),G(LTCS),G(LTREFU),G(LTMID),ECRIT1,PVRTC,ECUPLM,
\$STCHLM,IDNUM,TO,G(LZERCH))
IF(MX2EUS.LT.4) GO TO 110
40 WRITE(WT,902)
WRITE(WT,903) (J,J=1,NCYCIN)
WRITE(WT,904) (ELAME(I,J),J=1,NCYCIN)
WRITE(WT,905) (ELAME(2,J),J=1,NCYCIN)
WRITE(WT,906) (ELAME(3,J),J=1,NCYCIN)
WRITE(WT,907) (ELAME(4,J),J=1,NCYCIN)
DO 50 K=6,MX2EUS,2
WRITE(WT,506) (ELAME(K-1,J),J=1,NCYCIN)
50 WRITE(WT,907) (ELAME(K,J),J=1,NCYCIN)
80 DO 110 J=1,NCYCIN
NE2=NODES X2(N)
DO 90 I=4,NE2,2
90 ELAME(I-2,N)=(ELAME(I-2,N)-ELAME(I,N))/(ELAME(I-3,N)-ELAME(I-1,N)+1.E-20)
110 IF(.NOT.INCCST) GO TO 100
WRITE(WT,511)
WRITE(WT,519) IRCRS,IDNUM
WRITE(WT,902) PVRTC,(G(L+J),J=1,NCYCIN)
WRITE(WT,518) (ECUPLM(J),J=1,NCYCIN)
WRITE(WT,903) (J,J=1,NCYCIN)
WRITE(WT,904) (ELAME(1,J),J=1,NCYCIN)
WRITE(WT,915) (ELAME(2,J),J=1,NCYCIN)
WRITE(WT,916) (ELAME(3,J),J=1,NCYCIN)
WRITE(WT,917) (ELAME(4,J),J=1,NCYCIN)
CO 60 K=6,MX2EUS,2
WRITE(WT,917) (ELAME(K-1,J),J=1,NCYCIN)
60 WRITE(WT,917) (ELAME(K,J),J=1,NCYCIN)
110 CONTINUE
RETURN
900 FORMAT('1/* THIS ITERATION USES',I5,' LOCATIONS IN G ARRAY', $' COMPARED TO THE',I5,' AVAILABLE',/0')
901 FORMAT('1*T25,** ** ** REACTOR TOTAL COSTS RELATIVE TO R.T.C.', $' FCR ECRAL (1000 P.V.$) ** ** ** ')
902 FORMAT('C'TIJ, 'REACTOR TOTAL COST FOR BALANCED EC''S (ECBAL) = ', $'12.3', 10**3P.V.$/*ECBAL',14F9.1/(12X,12F9.1))
903 FORMAT('C CYCLE',14((I6,3X)/(12X,12(I6,3X))))
904 FORMAT('C EC',14F9.2/(12X,12F9.2))
905 FORMAT(' C DELRTC',14F9.2/(12X,12F9.2))
SUBROUTINE REDCOR
READ INPUT DATA FOR INCORE
CKCORE VERSION 12-15-72
COMMON/ARDATA/IDNO(15),NAME(15),MWCAP(15),EFFNET(15),IRCRKAL(15),
$IFULK(15),NCZCNE(15),ZCNKG(15),DECRT(15),DESTCH(15),NCYCFX(15),
$EPFX(20,15),BPSRT(10,15),FABINV(10,15),SRCINV(10,15),
$POWRF(10,15),RCRCCN(18,15),FUPLEG(15),EFFINC(15),
COMMON/FXCDAT/MXZONE,MXCYT,MXCRS,MRXCRK,MXFULK,IRCRR,IRCRL,IFULK,
$MCRS,NCRKR,NCFUK,EFF,XX,XRAT,TPRATE,TPBASE,TPPRE,TPST,
$ETY2F,CCRATE,FCOR,FFAB,FSAR,FCRE,NCYCN,NCYCX,NCYCTO,NZONE,NZP,
$ZONLEK,EDCHD,EFV,AW,WS,
COMMON/PRINTS/RELCLST,INCCST,BALCST,NBLCST,PIRDAT,PEATCS,RO,WT,
LOGICAL RELCLST,INCCST,BALCST,NBLCST,PIRDAT,PEATCS
INTEGER RO,WT
COMMON*16 HD(7)/ $LB U308 $, $/KG U CON$ $, $/KG SWU $,
$/KG FAB $ $, $/KG SHREP $, $/KG CCN$ $, $/GM FIS. FQ$,$
DATA $INCO$, $ENCB$ $, 'INCO', 'END' /
DIMENSION RCRKTL(20,15),FULKTL(20,5),
DIMENS RON X(20),ECTITL(20),A0(7),A1(7),A2(7),XX(20)
READ(RO,903) XX
WRITE(WT,931) XX
IF(XX(1).NE.$INCO$) CALL ICERRS('REDCOR',3)
READ (RO,901) NUECON,IRCRR,NUCRCR,NUCULK,RELCLST,INCCST,BALCST,
$NBLCST,PIRDAT,PEATCS
WRITE(WT,902) NUECON,IRCRR,NUCRCR,NUCULK,RELCLST,INCCST,BALCST,
$NBLCST,PIRDAT,PEATCS
IF (NURCRS.GT.MXRCRS.OR.NURCRK.GT.MXRCRK.OR.NUFULK.GT.MXFULK)
CALL ICERRS(*REDCOR*,5)
IF (NUECON.LE.0) GO TO 20
C READ ECONOMIC DATA
READ(RD,903) ECTYPEL
READ(RD,908) XF,XW,TXRATE,PVDATE,TBASE,DTPRE,DTPST,DTY2F6
10 I=1,7
READ(RD,508) AO(I),AI(I),A2(I),F
IF (I.EQ.2) FCOR=F
IF (I.EQ.4) FFAB=F
IF (I.EQ.5) FSAR=F
IF (I.EQ.6) FCRE=F
10 CONTINUE
X(11)=100.*XF
C INITIALIZE & SET POINTERS WHERE POSSIBLE
DUMMY=PVINIT(PVDATE)
CALL INIT(AO,A1,A2,DTPRE,DTPST,TBASE,X)
DUMMY=SETUVL(DTY2F6,FCCR,XF,XW)
X(12)=UF6VAL(X(11),X(1),X(2),X(3))
20 WRITE(WT,905) ECTYPEL
WRITE(WT,907) XF,XW,TXRATE,PVDATE,TBASE,DTPRE,DTPST,DTY2F6,
FCCRATE,X(8),X(9),X(10)
WRITE(WT,909) FCOR,FFAB,FSAR,CRE,(AO(I),AI(I),A2(I),X(I),
F)(I),I=1,7,X(12)
IF (NURCRS.LE.0) GO TO 40
C CALL ERASE REACTOR PHYSICAL INFO.
NRCRS=NURCRS
CALL ERASE(EPRFX,20*15)
DO 30 I=1,NRCRS
READ(RD,910) IDNO(I),NAME(I),MWCAP(I),IRCRA(I),IFULKA(I),
ZONCE(I),ZONKG(I),EFFNET(I),DECRT(I),DESTCH(I),EFFINC(I)
IF(EFFINC(I).LT.0.2) EFFINC(I)=EFFNET(I)
READ(RD,911) N,(EPFFX(I+J,I),J=1,N)
NCYCFX(I)=N
N=NCZONE(I)
IF(N.GT.MXZONE) CALL ICERRS('REDCOR',5)
30 READ(RD,912) (EPFSRT(J,I),BSRT(J,I),FABINV(J,I),SRCINV(J,I),
$POWFR(J,I),J=1,N)
40 WRITE(WT,913) NRCRS
DO 60 I=1,NRCRS
WRITE(WT,914) IDNR(I),NAME(I),MWCAP(I),IRCRKA(I),IFULKA(I),
$NOZONE(I),ZCNGK(I),EFFNET(I),DECRIT(I),DESTCH(I),EFFINC(I)
N=NCYCFX(I)
WRITE(WT,915) N,(EPFFX(I+J,I),J=1,N)
N=NCZONE(I)
WRITE(WT,916) (J,EPFSRT(J,I),BSRT(J,I),FABINV(J,I),SRCINV(J,I),
$POWFR(J,I),J=1,N)
SUM=0.
CO 50 J=1,N
50 SUM=SUM+POWFR(J,I)
IF(ABS(SUM-1.).GT.1.E-5) CALL ICERRS('REDCOR',9)
60 CONTINUE
IF(NURCRK.LE.0.) GO TO 70
C READ REACTOR EMPIRICAL CONSTANTS
NURCRK=NURCRK
READ (RD,917) ((RCRKLK(K,I),K=1,20),(RCRCON(J,I),J=1,18),
$1=1,NURCRK)
70 WRITE(WT,918) (I,(RCRKLK(K,I),K=1,20),(RCRCON(J,I),J=1,18),
$1=1,NURCRK)
IF(NUFULK.LE.0.) GO TO 80
C READ FUEL EMPIRICAL CONSTANTS
NUFULK=NUFULK
READ (RD,919) ((FULKTL(K,I),K=1,20),(FULCON(J,I),J=1,48),
$1=1,NUFULK)
80 WRITE(WT,920) (I,(FULKTL(K,I),K=1,20),(FULCON(J,I),J=1,48),
$1=1,NUFULK)
READ(RD,903) XX
WRITE(WT,932) XX
IF(XX(1).NE.$ENDB$) CALL ICERRS('REDCOR',3)
RETURN
901 FORMAT(415,6L1)
902 FORMAT('** ** ** ** ECONOMIC DATA ** ** ** **',
$10,T10,1H',23A4,1H'$)
903 FORMAT(20A4)
904 FORMAT('O'/0,TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
905 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
906 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
907 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
908 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
909 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
910 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
911 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
912 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
913 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
914 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
915 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
916 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
917 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
918 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
919 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
920 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
921 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
922 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
923 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
924 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
925 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
926 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
927 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
928 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
929 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
930 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
931 FORMAT('O',TF35,'** ** ** ** ECONOMIC DATA ** ** ** **/',
$T10,1H',23A4,1H'$)
SUBROUTINE FULSIM(MXESX2,NJESX2,ELAME,NECBAL,EPFSRT,EPFFX,BSRT,
$FOMFRC,TST,DTIC,MCDDIR,UTYEL,UNTCOR,UNTSU,UNTFAB,UNTSAR,UNTCRE,
$UNTPUV,PVFAG,EC,PVTCYC,TCCYC,ACUCYC,TCOECD,ACECD,EPF,B,BATCST,C,
$TREFUL,TMID,ECEAL1,BALRT,ECUPLM,STCHLM,IONUM,TO,ZEROHT)
PERFORMS FUEL IRRAC. SIMUL. FOR ALL SETS OF E'S  
CCMPCN/FXDDAT/MXZONE,MXCYTO,MRCCS,MRCRK,MXFVULK,IRCRI,IRCRI,IFULK
$NRCS,IRCRK,IFULK,EFF,EF,XR,FXRT,PRVATE,TBASE,DTPRE,DTST,
$CTY2FO,CCRTE,FCOR,FFAB,FSAR,FCRE,NCYCIN,NCYCXS,NCYCTO,NZONE,NZP,
$ZONEKG,ECHDUV,EFFAV,MS
COMMON/PRINTS/RELCS,INCCST,BALCDT,NBLCST,PIRDA,VA,MATCS,RT,WT
INTEGER RELCS,INCCST,BALCDT,NBLCST,PIRD,VA,MATCS,RT,WT
DIMENSION NOESX2(NCYCTO),ELAME(MXESX2,NCYCTO),NECBAL(NCYCTO),
$EPFSRT(NZONE),EPFFX(NCYCTO),BSRT(NZONE),TS(NCYCTO),
$TE(NCYCTO),DTNC(NCYCTO),MODDIR(NCYCTO),UNTYEL(NCYCTO),UNTCOR(NCYCTO)
$,UNTSU(NCYCTO),UNTFAB(NCYCTO),UNTSAR(NCYCTO),UNTCRE(NCYCTO),
$UNTPUV(NCYCTO),PVFACT(NCYCTO),EC(NCYCTO),TCCYC(NCYCTO),
$ACUCYC(NCYCTO),TCOECD(NCYCTO),ACECD(NCYCTO),EPF(NZP,NCYCTO),
$NZP,NCYCTO),BATCST(NZP,NCYCTO),PVTCYC(NCYCTC),CNZP
DIMENSION TO(NCYCTO),LEROHT(NCYCTO)
REAL*8 TCCYC,PVTCYC,SUM,RTCBALRT
INTEGER CYCFR,SCYCFR,SEABAT,SEBT
ZTCA=ZONEKG*0.001
BALRT=0.00
CALL CCNSTS(NCYCTO,TE,UNTYEL,UNTCOR,UNTSU,UNTFAB,UNTSAR,UNTCRE
$,UNTPUV,DTNC,PVFACT,TBASE,TREFUL,TMID)
FRSCYC=1
LSTCYC=NCYCTO
FRSET=1
FRSTRAT=NCYCIN+MINO(NZCNE,NCYCXS)
CALL ERASE(ECUPLM,NCYCTO)
ECUPLM(1)=ECE1A1+STCHLM
DO 10 CYC=1,NCYCTO
ZEROTH(CYC)=MWS*(1./EFFAV-1./EFF)*TO(CYC)*8.760
IF(EPPFX(CYC)) MODIRR(CYC)=2,1,3
1 MODIRR(CYC)=1
GC TC 10
2 MODIRR(CYC)=2
GO TO 10
3 MODIRR(CYC)=3
10 EC(CYC)=ELAME(2*NECBAL(CYC)-1,CYC)
MODIRR(1)=0
IF(NCYCXS.EQ.0) GO TO 20
$=1.20
NCP=NCYCIN+1
DO 15 I=NCP,NCYCTO
PVTCYC(I)=$
TCCYC(I)=$
ACCYC(I)=$
DO 15 N=1,NZP
15 BATCST(N,1)=$
20 DO 50 CYC=FRSCYC,LSTCYC
IF(PIRCAT.AND.CYC.EQ.FRSCYC) WRITE(WT,901) ICRS,IDNUM
MODE=MODIRR(CYC)
ECESPC=EC(CYC)
ECTSPC=ECESPC/EFF+ZEROTH(CYC)
EPFSPC=ABS(EPPFX(CYC))
IF(PIRCAT) WRITE(WT,900) CYC,ECTSPC,ECESPC
IF(CYC.EQ.1) GO TO 30
CALL NXTIRR(MODE,ECTSPC,EPFSPC,ZONEKG,NZCNE,EPF(1,CYC),B(1,CYC),
$=2,CYC+1),PIRCAT,WT,ECTCRT)
IF(BALRTC.EQ.0.0.AND.MODE.NE.1.AND.ECUPLM(CYC).EQ.0.0)
$ ECUPLM(CYC)=EFF*(ECTCRT-ZEROTH(CYC))+STCHLM
IF(MODE.EQ.2) EC(CYC)=EFF*(ECTSPC-ZEROTH(CYC))
22  IF(1, CYC+1)=.0
    DO 25 I=1, NZONE
25    EPF(I+1, CYC+1)=EPF(I, CYC)
    GO TO 50
30  DO 40 I=1, NZONE
30    EPF(I, 1)=EPSRT(I)
40    B(I, 1)=BSRT(I)
    IF(NZP, 1)=1.0E0
    CALL FRSIRR(MODE, ECTSC, ZONEKG, ECE1A1/EFF+ZERCHT(CYC), NZCNE, $EPF(1, CYC), B(1, CYC), B(2, CYC+1), PIRDAT, WT, POWFRC)
    GO TO 22
50  CONTINUE
    IF(PBATCS) WRITE(WT, 902) IRCRS, IDNUM
    CALL CSTBAT(BAT, NIRRAD)
    NIP=NIRRAD+1
    M1=MAX(0, NZONE-BAT)
    M2=MAX(BAT-NZONE, C)
    DO 60 I=1, NIP
60    BATCST(I+M1, I+M2)=C(I)*ZTON
    TCEOCD(BAT)=TCEOCD(BAT)*ZTON
    EATCST(NZP, 1)=.0
    DO 85 CYC=1, NCYCIN
     SUM=0.0
    DO 80 I=1, NZP
80     SUM=SUM+BATCST(I, CYC)
    TCCYC(CYC)=SUM
    ACCYC(CYC)=SUM/EC(CYC)
    IF(FRSBAT.LE.NCYCIN.AND.LSTBAT.GE.NCYCIN) $ TCCYC(NCYCIN)=TCCYC(NCYCIN)*{1.-ECHDOV/EC(NCYCIN)}
    RTC=0.0
    DO 90 CYC=1, NCYCIN
85    PVTYC(CYC)=TCCYC(CYC)*PVFAC(CYC)
90    RTC=RTC+PVTYC(CYC)
IF(BALRTC.GT.0.0D0) GO TO 100
IF(.NOT.NBLCST.AND..NOT.NBLCST) GO TO 150
CALL PRTTOP(NZP,NCYCTC,WT,TS,TE,RTC,MODIR,UNTYEL,UNCTOR,UNTSWU,
$UNTFAB,UNTSAR,UNTCRE,UNTPVU,PFVACT,EC,PVTCYC,TCCYC,ACCYC,TCECD,
$ACECCD,EF,P,BATCS,TREFUL,TMID,NCYCIN,ECHDOV,IRCST,IDNUM)
GO TO 110
100 IF(.NOT.NBLCST) GO TO 20C
110 CALL PRTBTM(RTC)
   IF(BALRTC.GT.0.0D0) GC TO 200
150 EALRTC=RTC
   DO 180 N=1,NCYCIN
   NCYC=NCYCIN-N+1
   ECFAL=EC(NCYC)
   IF(MODIRR(NCYC).EQ.2) GO TO 180
   NE2=NOESX2(NCYC)
   FRSCYC=NCYC
   LSTCYC=NCYCTO
   FRSBAT=FRSCYC
   LSTRAT=NCYCIN+MINO(NZCNE,NCYCXS)
   DO 170 J=1,NE2,2
   EC(NCYC)=ELAME(J,NCYC)
   RTC=BALRTC
   IF(EC(NCYC).EQ.ECBAL) GO TO 160
   GO TO 190
160 ELAME(J+1,NCYC)=RTC-BALRTC
170 CONTINUE
180 EC(NCYC)=ECBAL
   RETURN
190 GO TO 20
200 GO TO 160
900 FORMAT(901*C/*'OCTLE ',I2,9X,'ECTSPC =',F10.2,' GWHTH',10X,
$'ECESPC =',F10.2,' GWHHE' )
901 FORMAT(902*1*'OCTLE IRRADIATION DATA FOR ',I3,' TH REACTOR (IDNO =
$*,I5,*') :*/)
902 FORMAT(903*1*'OCTLE CRAFT COSTS FOR ',I3,' TH REACTOR (IDNO =
$*,I5,*') :*/)
SUBROUTINE CONSTS(NCYCTO, TS, UNTYEL, UNTCOR, UNTSWU, UNTFAB,
$\$LNT, SAR, UNTCRE, UNTPUV, DTC, PVFACT, TBASE, TREFUL, TMID)
CALCULATE CONSTANT DATA FOR THIS ITERATION THRU INCORE

C VERSION 3-04-72

DIMENSION TS(NCYCTO), TE(NCYCTO), COST(7)
C DIMENSION DTC(NCYCTO), PVFACT(NCYCTO), UNTYEL(NCYCTO), UNTCOR(NCYCTO)
$\$, UNTSWU(NCYCTO), UNTFAB(NCYCTO), UNTSAR(NCYCTO), UNTCRE(NCYCTO),
$\$LNPVU(NCYCTO), TREFUL(NCYCTO), TMID(NCYCTO)

REAL*8 PVPER$
TEMP=TS(NCYCTO+1)
TS(NCYCTO+1)=TE(NCYCTO)+TS(NCYCTO)-TE(NCYCTO-1)
I=1
TSRT=TS(1)
100 CALL UNTCCS(TSRT, CCST)
UNTYEL(I)=COST(1)
LNTCCR(I)=COST(2)
UNTSWU(I)=COST(3)
UNTFAB(I)=COST(4)
UNTSAR(I)=COST(5)
UNTCRE(I)=COST(6)
LNPVU(I)=COST(7)
TSRTNX=0.5*(TE(I)+TS(I+1))
CTC(I)=TSRTNX-TSRT
TMD=TSRT+0.5*DTC(I)
PVFACT(I)=PVPER$(TMC, TBASE)
TREFUL(I)=TSRT
TMIC(I)=TMD
TSRT=TSRTNX
I=I+1
IF(I.LE.NCYCTO) GO TO 100
TS(NCYCTO+1)=TEMP
RETURN
END

SUBROUTINE NXTIRR(MODE, ECSPC, EPFSPC, ZONEKG, NZCNE, EPF, BGIN, BFNL,
$\$\$ PRINT, NPNTR, ECTCRT)
PERFORMS SIMULATION OF NEXT IRRADIATION

CQKCORE VERSION 3-J4-72
C
C ALL EC'S IN UNITS OF GWH/T FROM THE ENTIRE REACTOR
C
C MODE = 0 FIRST CYCLE WHICH IS ALREADY UNDERGOING IRRADIATION
C THEREFORE ONLY FRSIRR CAN BE CALLED
C
C = 1 EC SPECIFIED; EPFNEW TO BE DETERMINED
C = 2 EPFNEW SPECIFIED; EC TO BE DETERMINED
C
C = 3 EC & EPFNEW SPECIFIED (STRETCHCUT OR EARLY REFUELING)

IMPLICIT REAL (K)

ICAL PRINT

IMENSION EPF(NZONE),BGIN(NZONE),BFNL(NZONE)
IMENSION K8(10),SIGA(10),DB(10),F(10)
COMMON/IRRDAT/K8INR,ECOUT,ECRIT,UTIL,EC$24Z,K8,SIGA,DF,F
DATA EPFMIN,EPFMAX/1.5,5.0/
IF(MODE.EQ.0) CALL ICERRS('NXTIRR*',12)
K8INR=0.0
LTL=1.0
FSUM=0.0
IF(NZONE.EQ.1) GO TO 30
TEMP=0.0
20 CO 20 N=2,NZONE
E=EPF(N
B=BGIN(N
K8(N)=FK8(E,B)
SIGA(N)=FSIGA(E)
F(N)=SIGA(N)*K8(N)
FSUM=FSUM+F(N)
TEMP=TEMP*K8(N)
K8INR=TEMP/(NZONE-1)
30 IF(MODE.GT.1) GO TO 80
K81=FK8NEW(ECSPC,K8INR)
K8(1)=K81
EPF1=EPF(K81)
IF(EPF1.GT.EPFMAX.OR.EPF1.LT.EPFMIN) GO TO 100
EPF(1)=EPF1
ECOLT=ECSPC
ECRIT = ECSPC

40 EPF1 = EPF(1)
    FHI = FPHI(EPF1, K8INR)
    SIGA(1) = FSIGA(EPF1)
    F(1) = SIGA(1) * K8(1) * PHI
    TEMP = 1.0 / (FSUM + F(1))

50 EC$24Z = ECOUT / (24.0 * ZCNEKG * 0.001)
    CO 70 N = 1, NZCNE
    F(N) = F(N) * TEMP
    CB(N) = F(N) * EC$24Z

70 BFNL(N) = BGIN(N) + DB(N)
    ECTRIT = ECRIT
    IF (.NOT. PRINT) RETURN
    NZ = NZONE
    WRITENPRNTR, 900) MODE, ECSPC, EPFSPEC, ZONEKG, K8INR, EC$24Z, ECOUT, ECRIT, UTIL, (N, EPF(N), BGIN(N), DB(N), BFNL(N), KE(N), SIGA(N), F(N), N = 1, NZ)
    RETURN

80 EPF(1) = EPFSPEC
    E = EPF(1)
    B = BGIN(1)
    K81 = FK8(E, B)
    K8(1) = K81
    ECRIT = FECOUT(K81, K8INR)
    IF (MCDE .GT. 2) GO TO 85
    ECOUT = ECRIT
    ECSPC = ECOUT
    GO TO 40

85 ECOUT = ECSPC
    UTIL = ECOUT / ECRIT
    C CHECK FOR WARNING OF TOO MUCH STRETCHOUT ENTRY FRSIR(1.25)
    IF (UTIL .GT. 1.25) CALL ICERRS('NXTIRR', 1)

    C CHECK FOR WARNING OF VERY LITTLE IRRADIATION ENTRY FRSIR(1.75)
    IF (UTIL .LT. 0.75) CALL ICERRS('NXTIRR', 2)
    GC TO 40

    C COMPLETE FIRST CYCLE IRRADIATION ENTRY FRSIR(MODE, ECSPC, ZONEKG, EKRT, NZONE, EP, BGIN, BFNL, PRINT,
$NPRNTR,POWFRC)
DIMENSION POWFRC(NZONE)
ECRIT=EKRIT
EPFSPC=0.0
K8INR=0.0
EOLIT=ECSPC
UTIL=ECOUT/ECRIT
TEMP=1.0
DO 90 N=1,NZONE
F(N)=POWFRC(N)
K8(N)=0.0
SIGA(N)=CJ
GO TO 50
100 MODE=3
EPFSPC=EPFMIN
IF(EPFI.GT.EPFMAX) EPFSPC=EPFMAX
CALL ICERRS('NXTIRR',11)
GO TO 80
90 FORMAT('0MODE =',I2,10X,'ECSPC =',F10.2,' GWHTH
$','10X,'EPFSPC =',F10.5,'10X,'ZONEKG =',F10.1/0 'K8INR =',F10.6,5X,
$','EC24Z =',F10.4,5X,'ECOUT =',F10.2,5X,'ECRIT =',F10.2,5X,'UTIL ='
$,F10.6/8C N EPF BGIN DB BFNL K8',
$6X,' SIGA F/(13,F10.6,3F10.4,3F10.6))
END
SUBROUTINE CSTBAT(LSTIRR,NIRRAD)
C CALCULATE COST OF BATCH DISCHARGED AT END OF LSTIRR AND WHICH WAS
C IRRADIATED NIRRAD TIMES WITHIN THE SIMULATION
C QKCORE VERSION 12-15-72
C IMPLICIT REAL (K)
COMMON/FXDDAT/MXZONE,MXYTO,MRXCRS,MRXCRK,MXFULK,IRCRR,IRCRRK,IRFULK
$,NRCHR,MRCHR,NFULK,EFF,XF,XH,TXRAT,PVRAT,TBASE,DTPRE,DTPST,
$DTY2F6,CCRAT,FCR,FFAB,FSAR,FCRE,NCYCN,NCYCX,NCYCTO,NZONE,NZP,
$ZONEKG,EC-DVO,EFFAV,MAS
COMMON/PRNTS/RELCST,INCCST,BALCST,NBLCST,P出租,PRATCS,RO,WT
LOGICAL RELCST,INCCST,BALCST,NBLCST,P出租,PRATCS
INTEGER RE,WT
INTEGER FRSIRR
REAL IUF6, IFAB, ISRC, IPUV, ITOT
REAL*8 P VPER$
LOGICAL NEWFUL
GO TO 5
ENTRY INIT3 (FABINV, SRCINV, EPF, DTC, B, UNTYEL, UNTCOR, UNTSWU, UNTFAB,
$ LNTSAR, UNTCRE, UNTPUV, TCEOCD, AEOCD, A, BC, CBC, DT, KGU, EPNOW, UVALUE,
$ GMP, IUF6, IFAB, ISRC, IPUV, ITOT, C, AC)
DIMENSION FABINV(NZONE), SRCINV(NZONE)
DIMENSION EPF(NZP, NCYCTC), DTC(NCYCTC), B(NZP, NCYCT0), UNTYEL(NCYCT0),
$ UNTCOR(NCYCTO), UNTSWU(NCYCTO), UNTFAB(NCYCTO), UNTSAR(NCYCTO),
$ UNTCRE(NCYCTO), UNTPUV(NCYCTO), TCEOCD(NCYCTO), AEOCD(NCYCTO),
DIMENSION A(NZP, 15), BC(NZP), CBC(NZP), DT(NZP), KGU(NZP),
$ EPNOW(NZP), UVALUE(NZP), GMP(NZP), IUF6(NZP), IFAB(NZP), ISRC(NZP),
$ IPUV(NZP), ITOT(NZP), C(NZP), AC(NZP)
CCPRE = DTPRE * CCRATE
CCPST = DTPST * CCRATE
FABLCS = (1. - FFAB) / FFAB
SARLOS = 1. - FSAR
CRELCS = FSAR * (1. - FCRE)
RETURN
5 CALL ERASE (A, 15*NZP)
NI = NIRRAD
MPI = NIRRAD + 1
MNI = NI RRAD - 1
NEWFUL = * TRUE.*
FRSIRR = LSTIRR - NZONE + 1
IF (FRSIRR.GT.1) GO TO 10
FRSIRR = 1
NEWFUL = * FALSE.*
10 EPFAB = EPF(NZONE, LSTIRR)
JCYCL = FRSIRR - 1
JZCNE = NZCNE - NI
do 20 i=1, NI
A(i, 1) = 1
JCYCL = JCYCL + 1
20
JZCNE = JZCNE + 1
CT(I) = DTC(JCYCL)
BC(I) = B(JZCNE + 1, JCYCL + 1) - B(JZONE, JCYCL)

20 BC(I) = B(JZONE, JCYCL)
BC(NIP) = BC(NI) + O8C(NI)
BC(NIP) = 0.0
CT(NIP) = 0.0
CO 30 I = 1, NIP
BURN = BC(I)
KGU(I) = FKGUR(EFPAB, BURN)
EPNOW(I) = FEPB(EFPAB, BURN)
GMP(I) = FKGPU(EFPAB, BURN) * 1000.
LVALUE(I) = UF6VAL(EPNOW(I), UNTYEL(FRSIRR), UNTCCR(FRSIRR), UNTSWU(FRS
$I$RR))
IUF6(I) = UVALUE(I) * KGU(I)

30 IPUV(I) = UNTPUV(LSTIRR) * GMP(I)
IFAR(I) = UNTFAB(FRSIRR) * FABLOS * IUF6(I)
ISRC(I) = C.*0
IF (NEWFUL) GO TO 40
JZCNE = NZCNE - NI + 1
IFAB(I) = FABINV(JZONE)
ISRC(I) = SRCINV(JZONE)

40 ISRC(NIP) = UNTSAR(LSTIRR) * (KGU(NIP) + 0.001 * GMP(NIP))
$ + SARLOS * (IUF6(NIP) + IPUV(NIP))$
$ + UNTCRE(LSTIRR) * KGU(NIP) * FSAR * CRELOS * IUF6(NIP)
DISRC = ISRC(NIP) - ISRC(I)
CVDB = 1. / (BC(NIP) - BC(I))
CO 50 I = 1, NIP
F = (BC(I) - BC(I)) * CVCB
IFAB(I) = IFAB(1) * (1. - F)
ISRC(I) = ISRC(I) * DISRC * F

50 ITOT(I) = IUF6(I) + IFAB(I) - ISRC(I) + IPUV(I)
CO 60 I = 1, NI
C(I) = ITOT(I) - ITOT(I+1) + (ITOT(I) + ITOT(I+1)) * 0.5 * DT(I) * CCRATE
IF (LSTIRR.GT.NIPRAC) C(I) = C(I) + ITOT(I) * CCPRE
C(NIP) = ITOT(NIP) * CCPST
TWCTPV=0.0
N=1
70 IF(N.EQ.NI) GO TO 80
N=N+1
TWOTPV=TWOTPV+DT((N+1)/2)
GO TO 70
80
TCBAT=0.0
PVRBN=0.0
CO 90 I=1,NI
FVPER=PVPERS(-0.5*TWOTPV,0.0)
TCBAT=TCBAT+C(I)*PVPER
PVRBN=PVRBN+CBC(I)*PVPER
AC(I)=C(I)/(24.*EFFAV*DBCT(I))
GO TC 70
90
TWCTPV=TWCTPV-PI/(I+DT(I+1))
TCBAT=TCBAT+C(NIP)*PVPER(-0.5*TWOTPV,0.0)
AC(NIP)=1.E20
PVELEC=PVRBN*24.*EFFAV
ACEOCD(LSTIRR)=TCBAT/PVELEC
TCECCD(LST)=TCBAT
LST=LSTIRR
IF(PBATCS) WRITE(WT,90) LSTIRR,NIRRAD,TCBAT,PVELEC,ACEOCD(LST),
$(((A(I,J),J=1,15),I=1,NIP)
RETURN
900 FORMAT('01/10X,'"COST OF BATCH DISCH. AT END OF CYCLE",I3,
" WHICH WAS IRRADIATED FOR",I3," CYCLES OF THE SIMULATION :/
" TOTAL COST OF DISCHARGED BATCH (P.V. AT MID-PT. OF MIDDLE',
" IRRAD.) =",F8.2,' $/KGFA6'/' AVERAGE COST FOR THE',F8.2,
" MWHE/ KGFA6 (ALSO P.V.)',T70 ;'=',F8.4,' $/MWHE'
" I BC CBC DT KGUR ENRICH UF6VAL GMSPU',
" UF6 FAB SRC PUV TOTINV CST AVGST'/'
" MW/ KGFA6 MWD/ KGFA6 YRS KG/KGFA6 W/0235 $/KGUF6 GM/KGFA6'
" T67,'---- DOLLARS PER KILOGRAM FABRICATED ---- $/MWHE'
END
SUBROUTINE PRITOP(AZP,NCYCTO,WT,TS,TE,RTC,MODIRR,UNTYEL,UNCTOR,
$)LNTSWU,UNTFAB,UNTSAR,UNCTRE,UNTPUV,PFVFACT,EC,PVTYC,TCCYC,ACCY,
PROGRAM TCEOCO

C PRINT TOP OF FULSIM RESULT TABLE
C
C CKCORE VERSION 3-04-72
REAL*8 TCCYC, PVTCYC, RTC
DIMENSION TS(NCYCTO),
$TE(NCYCTO), DTC(NCYCTO), MCDIRR(NCYCTO), UNTIEL(NCYCTO), UNTCOR(NCYCTO),
$%, UNTSWU(NCYCTO), UNTFAB(NCYCTO), UNTSAR(NCYCTO), UNTCRE(NCYCTO),
$LNPVU(NCYCTO), PVFACT(NCYCTO), EC(NCYCTO), TCCYC(NCYCTO),
$ACCYC(NCYCTO), TCEOCO(NCYCTO), ACEOCO(NCYCTO), EPF(NZP,NCYCTO),
$B(NZP,NCYCTO), BATCST(NZP,NCYCTO), PVTCYC(NCYCTO), TREFUL(NCYCTO),
$TMID(NCYCTO)
COMPLEX*16 HD(60), BLANK, E1, NP1, B1, $1
INTEGER WTFRS
CATA
HD/I CYCLE', ' TIRSRT YRS', ' TIREND YRS', ' DTREF. YRS',
$' MCDIRR', ' UNTIEL $/LBY', ' UNTCOR $/KG', ' UNTSWU $/KGS',
$' UNTFAB $/KG', ' UNTSAR $/KG', ' UNTCRE $/KG', ' UNTPV $/GMP',
$' PVFACT $/TMID', ' OEC GWHE', ' PVTCYC $/TCCYC', ' ACCYC $/MWH', ' TCEOCO $/TCCYC', ' ACEOCO $/MWH', ' TREFUL YRS', ' TMID YRS'/
CATA BLANK, E1, B1, $1, NP1/ ' ', EPF(1)', ' EGIN(1)', ' BATCST(1)',
$' (N+1)'/
FRS=22
LST=FRS+3*NZP-1
NZ=NZP-1
CO 10 I=FRS,LST
10 HD(I)= BLANK
HD(FRS)=E1
HD(FRS+NZ)=NP1
HD(FRS+NZP)=B1
HD(LST-NZP)=NP1
HD(LST-NZ)=NP1
WRITE(WT,930) IRCRS, IDNUM
WRITE(WT,901) HD(1), (I=NCYCTO)
WRITE(WT,914) HD(20), TREFUL
WRITE(WT,914) HD(4), DTC
WRITE(WT,914) HD(2), TS
WRITE(WT,914) HD(3),TE
WRITE(WT,901) HD(5),MCDIRR
WRITE(WT,914) HD(21),TMID
WRITE(WT,915) HD(13),PVFACT
WRITE(WT,902) '
WRITE(WT,912) HD(6),UNTYEL
WRITE(WT,912) HD(7),UNTCCR
WRITE(WT,912) HD(8),UNTSWU
WRITE(WT,912) HD(9),UNTFAB
WRITE(WT,912) HD(10),UNTSAR
WRITE(WT,912) HD(11),UNTCRE
WRITE(WT,912) HD(12),UNTPUV
RETURN
ENTRY PRTBTM(RTC)
PRINT BOTTOM OF FULSIM RESULT TABLE
WRITE(WT,931) IRCRS, IDNUM, RTC, NCYCIN, ECHDOV
WRITE(WT,901) HD(1), (I, I=1, NCYCTO)
WRITE(WT,912) HD(14), EC
WRITE(WT,912) HD(15), PVTCYC
WRITE(WT,912) HD(16), TCCYC
WRITE(WT,914) HD(17), ACCYC
WRITE(WT,912) HD(18), TCECCD
WRITE(WT,914) HD(19), ACECCD
IX=FRS-1
WRITE(WT,900)
CO 20 M=1,NZP
WRITE(WT,914) HD(M+IX), (EPF(M,I), I=1, NCYCTO)
IX=IX+NZP
WRITE(WT,900)
CO 30 M=1,NZP
WRITE(WT,914) HD(M+IX), (B(M,I), I=1, NCYCTC)
IX=IX+NZP
WRITE(WT,900)
CO 40 M=1,NZP
WRITE(WT,912) HD(M+IX), (BAT CST(M,I), I=1, NCYCTO)
RETURN
FUNCTION EMFRCL(F,R)
C INITIALIZE EMPIRICAL EQUATIONS
C QKCCRE VERSION 3-04-72
IMPLICIT REAL(K)
DIMENSION F(100),R(25)
C EVALUATE QUADRATIC \( Q = c_0 + c_1x + c_2x^2 \)
C \( f(c_0,c_1,c_2,x) = (c_2x+c_1)x+c_0 \)
C UNIT FUEL SIMULATION EQUATIONS
C SETUP INVERSION OF K8AEW TO GET EPFNEW
EMFRCL=0.0
IF(F(3).EQ.J.J) GO TO 10
CEF1=-0.5*F(2)/F(3)
CEF2=(F(2)**2-4.*F(3)*F(1))/(4.*F(3)**2)
CEF3=1./F(3)
CEF4=0.0
K8MAX=Q(F(1),F(2),F(3),CEF1)-1.E-5
RETURN
10 CEF1=-F(1)/F(2)
CEF2=0.0
CEF3=0.0
CEF4 = 1 / F(2)  
K8MAX = 100.  
RETURN

ENTRY FK8(EPF, B)  
FKE = Q(Q(F(1), F(2), F(3), EPF), Q(F(4), F(5), F(6), EPF),  
$G(F(7), F(8), F(9), EPF), B)  
RETURN

ENTRY FKGUR(EPF, B)  
FKGUR = Q(Q(F(10), F(11), F(12), EPF), Q(F(13), F(14), F(15), EPF),  
$G(F(16), F(17), F(18), EPF), B)  
RETURN

ENTRY FEPB(EPF, B)  
DUM = Q(Q(F(19), F(20), F(21), EPF), Q(F(22), F(23), F(24), EPF),  
$G(F(25), F(26), F(27), EPF), B)  
FEPB = EPF * EXP(-B * DUM)  
RETURN

ENTRY FKGPU(EPF, B)  
CUM = Q(Q(F(28), F(29), F(30), EPF), Q(F(31), F(32), F(33), EPF),  
$G(F(34), F(35), F(36), EPF), B)  
LLAM = Q(F(37), F(38), F(39), EPF)  
FLAM = Q(F(40), F(41), F(42), EPF)  
FKGPU = DUM * (EXP(-B * ULAM) - EXP(-B * PLAM))  
RETURN

ENTRY FSIGA(EPF)  
FSIGA = F(43) * F(44) * EPF  
RETURN

ENTRY FEPF(K8NEW)  
FEPF = 100.  
IF(K8NEW .GT. K8MAX) RETURN  
FEPF = CEF1 - SQRT(CEF2 + CEF3 * K8NEW) + CEF4 * K8NEW
RETURN
C***********************************************************************
C REACTOR IRRADIATION SIMULATION EQUATIONS
ENTRY FK8NEW(EC,K8INR)
DK=K8INR-1.
FK8NEW=1.*Q(R(1),R(2),R(3),EC)+Q(0.0,R(4)+R(6)*EC,R(5),DK)
RETURN
C***********************************************************************
ENTRY FPHI(EPF,K8INR)
DK=K8INR-1.
FPHI=1./(1.+EPF*Q(R(8),R(9),R(10),EPF)+Q(R(7),R(11),R(12),DK))
RETURN
C***********************************************************************
ENTRY FECOUT(K8NEW,K8INR)
C REWRITE K8NEW AS AA*EC**2 +BB*EC+CC=0 AND SOLVE FOR EC
CK=K8INR-1.
AA=R(3)
BB=R(2)+R(6)*DK
CC=Q(1.+R(1)-K8NEW,R(4),R(5),DK)
IF(AA.EQ.0.0) GC TO 20
FECOUT=BB*(SQRT(1.-4.*AA*CC/BB**2)-1.)/(AA+AA)
RETURN
20 FECOUT=-CC/BB
RETURN
END
SUBROUTINE UNTCOS(TREFUL,COST)
C CALCULATE ESCALATEC UNIT COSTS
C CKCRE VERSION 3-4-72
C DIMENSION COST(7),A0(7),A1(7),A2(7),B0(7),B1(7),B2(7)
GO TO 10
ENTRY INIT2(B0,B1,B2,DTPRE,DTPST,TREFUL,COST)
C INITIALIZE POINTERS AND DATA
DO 10 I=1,7
   A0(I)=B0(I)
   A1(I)=B1(I)
  5 A2(I)=B2(I)
10 TPRE=TREFUL-DTPRE
TPST=TREFUL+DTPST
CO 20 I=1,4
20 COST(I)=(TPRE*A2(I)+A1(I))*TPRE+A0(I)
CO 30 I=5,7
30 COST(I)=(TPST*A2(I)+A1(I))*TPST+A0(I)
RETURN
END
FUNCTION UF6VAL(/EP/,/UNTYEL/,/UNCOR/,/UNTSWU/)
C CALCULATES VALUE OF ENRICHED URANIUM AS $/KG UF6
C CKCORE VERSION 3-04-72
REAL*8 PVPER$
PHI(X)=(X+X-1.)*ALOG(X/((1.-X))
SOVP(X)=PHI(X)+A+B*X
FOVP(XP)=(XP-XW)*UVOX
CF=C1*UNTYEL+UNCOR
XP=0.01*EP
UF6VAL=CF*FOVP(XP)+UNTSWU*SOVP(XP)
RETURN
ENTRY SETUVL(DTY2F6,FCOR,XF,XW)
C SETUP URAN. VALUE EQUATION
C1=2.599E5*PVPER$(-DTY2F6,0.0)/FCOR
CVDX=1./(XF-XW)
PHIXF=PHI(XF)
PHIXW=PHI(XW)
A=(-XF*PHIXW + XW*PHIXF)*CVDX
B=(PHIXW-PHIXF)*CVDX
SETUVL=0.0
RETURN
END
FUNCTION PVPER$(T,TBASE)
C CALCULATE PRESENT VALUE AT TIME T OF 1$ AT TIME TBASE
C CKCORE VERSION 3-04-72
REAL*8 PVPER$,LN1PX
PVPER$=DEXP(-LN1PX*(T-TBASE))
RETURN
ENTRY PVINIT(PVRATE)
C PRE-CALCULATE LOG OF (1+X) IN UNITS OF INVERSE YEARS
LN1PX=DLOG(1.00+PVRATE)
PVINIT=LN1PX
RETURN
END
SUBROUTINE ICERRS(SUBR,JERR)
C WRITES OUT ALL ERROR MESSAGES FOR INCORE
C QKCORE VERSION 3-04-72
COMMON/PRINTS/RELCST,INCCST,BALCST,NBLCST,PIRDAT,PBATCS,RD,WT
LOGICAL RELCST,INCCST,BALCST,NBLCST,PIRDAT,PBATCS
INTEGER RC,WT
INTEGER ERRCOD
REAL*8 SUBR,$QUIT$
CATA NPRINT/0/$QUIT$/' CUIT'/,ERRCOD/0/,MAXERR/16777216/
C MAXERR=16**6
IERR=JERR
100 ERRCOD=MCD(ERRCOD,MAXERR)
ERRCOD=16*ERRCOD+IERR
NPRINT=NPRINT+1
GO TO (1,2,3,4,5,6,7,8,9,10,11,12),IERR
1 WRITE(WT,901) SUBR,ERRCOD,NPRINT
RETURN
2 WRITE(WT,902) SUBR,ERRCOD,NPRINT
RETURN
3 WRITE(WT,903) SUBR,ERRCOD,NPRINT
GO TO 1000
4 WRITE(WT,904) SUBR,ERRCOD,NPRINT
GO TO 1000
5 WRITE(WT,905) SUBR,ERRCOD,NPRINT
GO TO 1000
6 WRITE(WT,906) SUBR,ERRCOD,NPRINT
RETURN
7 WRITE(WT,907) SUBR,ERRCOD,NPRINT
GO TO 1000
8 WRITE(WT,908) SUBR,ERRCOD,NPRINT,NPRINT
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STCP
9 WRITE(WT,909) SUBR,ERRCCD,NPRINT
   RETURN
10 WRITE(WT,910) SUBR,ERRCCD,NPRINT
   GO TO 1000
11 WRITE(WT,911) SUBR,ERRCCD,NPRINT
   RETLAN
12 WRITE(WT,912) SUBR,ERRCCD,NPRINT
   GO TO 1000
1000 NPRINT=NPRINT+1
   WRITE(WT,999) NPRINT, SUBR=$QUIT$,
   IERR=8
   GO TO 100
901 FORMAT(/'**/130('**)/', '* SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
   '$ UTIL.GT. 1.25 VERY LONG STRETCHOUT ',
   '$ T131,*130('**),12)
902 FORMAT(/'**/130('**)/', '* SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
   '$ UTIL.LT.0.75 VERY EARLY REFUELING ',
   '$ T131,*130('**),12)
903 FORMAT(/'**/130('**)/', '* SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
   '** INPUT DECK HAS IMPROPER SEQUENCE &/OR CARD ',
   '$ T131,*130('**),12)
904 FORMAT(/'**/130('**)/', '* SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
    '** ARRAY G IN THIS VERSION IS TOO SMALL FOR THIS',
   '** PROBLEM ',
   '$ T131,*130('**),12)
905 FORMAT(/'**/130('**)/', '* SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
   '** TOO MANY ZONES, REACTORS, OR SETS OF REACTOR ',
   '** &/OR FUEL CCNSTANTS FOR THIS VERSION ',
   '$ T131,*130('**),12)
906 FORMAT(/'**/130('**)/', '* SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
   '** WARNING: NCYCCTC WAS NOT EQUAL TO NCYCIN ',
   '** & NCYCXS WHEN INCORE ENTERED ',
   '$ T131,*130('**),12)
907 FORMAT(/'**/130('**)/', '* SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
   **
$' REACTOR FOR CASE IDNUM NOT READ IN BY ICNPUT $',
$' T131,'*,/,' ,130('**'),12 $'
908 FORMAT(/',130('**)/,' * SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
$' QKCRE ENCODED STCP CARD; ICERRS CALLED ONE TOO OFTEN OR 0',
$' OTHER FATAL ERROR. ', T131,'*/' * DURING THIS ENTIRE RUN; ICERRS',
$' PRINTED A TOTAL OF ',13,' ERROR MESSAGES JUST LIKE (AND ',
$' INCLUDING) THIS ONE $',
$' T131,'*/' /',130('**),12 $'
909 FORMAT(/',130('**)/,' * SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
$' SUMMATION OF POWFRC DIFFERS FROM 1.0 BY MORE ',
$' THAN 10**-5 ',
$' T131,'*/' /',130('**),12 $'
910 FORMAT(/',130('**)/,' * SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
$' ELSE TABLE IS TOO LARGE FOR THIS VERSION. ',
$' T131,'*/' /',130('**),12 $'
911 FORMAT(/',130('**)/,' * SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
$' FEED ENRICHMENT AS DETERMINED IN NXTIRR UNDER ',
$' MODE 1; OUTSIDE PRESCRIBED LIMITS ',
$' T131,'*/' /',130('**),12 $'
912 FORMAT(/',130('**)/,' * SUBR. ',A6,' HAS ERRCOD = ',Z8,' : ',
$' NXTIRR CALLED WHEN MODE=0 (SHOULD CALL FRSIRR),
$' $'
$' T131,'*/' /',130('**),12 $'
999 FORMAT(/',130('**)/,' * PREVIOUS ERROR SEVERE ENOUGH TO ',
$' invalicate further computations. therefore ',
$' TERMINATING EXECUTION. ',
$' T131,'*/' /',130('**),12 $'
END

**** ************************************************************ 00000000 QKCR1189
* ASSEMBLER LANGUAGE SUBROUTINE ERASE
* WRITTEN BY JOHN W. KICSON
* MIT DEPARTMENT OF METEOROLOGY
* TO SET ELEMENTS OF REAL OR INTEGER ARRAYS TO ZERO. A1,A2,....
* ARE ARRAY NAMES AND N1,N2,.... ARE INTEGER VALUES OR
** QKCR1190 QKCR1191 QKCR1192 QKCR1193 QKCR1194 QKCR1195 QKCR1196 QKCR1197 QKCR1198 QKCR1199 QKCR1199 QKCR1200 QKCR1201 QKCR1202 QKCR1203 QKCR1204 QKCR1205 QKCR1206 QKCR1207 QKCR1208 QKCR1209 QKCR1210 QKCR1211 QKCR1212 QKCR1213 QKCR1214 QKCR1215 QKCR1216
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* EXPRESSIONS GIVING THE ARRAY SIZES.
** I.E. - CALL ERASE(C,26*31,N,7*31,E,254)
* ERASE
START 0
SAVE (14,12),*
EALK 12,0
LSING *,12
SR 0,0
SR 2,2
PARAMETER LIST INDEX=0
L 6,=F'4'
E1 L 3,0(2,1)
LOAD 3 WITH ARRAY ADDRESS
L 4,4(2,1)
LOAD 4 WITH ADDRESS OF ARRAY LENGTH
L 7,0(4)
LOAD 7 WITH ARRAY LENGTH-1 TIMES 4
SLA 7,2
SR 7,6
SR 5,5
E2 ST 1,0(5,3)
STORE ZERO
BXLE 5,6,E2
LTR 4,4
TEST FOR LAST ARGUMENT IN LIST
BM RETN
A 2,=F'8'
PICK UP NEXT ARGUMENT PAIR
B E1
RETN
RETURN (14,12),T
END