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A DYNAMIC PROGRAMMING ALGORITHM
OF THE
UNITED STATES URANIUM-235
PRODUCTION FACILITIES

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A DYNAMIC PROGRAMMING ALGORITHM OF THE
UNITED STATES URANIUM-235 PRODUCTION FACILITIES

ABSTRACT

The Atomic Energy Commission has three gaseous diffusion plants in operation. This production complex was constructed at a cost exceeding \$2 billion. The principal product from this complex is uranium enriched in the 235 isotope. Various enrichments of uranium are used as fuels in nuclear-fission reactors. These reactors use their fuel to produce electric power and radioactive isotopes.

A mathematical model of this production complex has been formulated in order to assist in conducting a more effective analysis of this economic system. Use of this particular model is not the only mode of analysis in this area of endeavor; however, it is one of the more comprehensive. Primarily, it is used to gain more insight into the encompassing environment and to provide a basis for further studies. The model is designed within the framework of dynamic programming and utilizes the backward algorithm with analytic stage solutions.

The purpose of this report is to describe how this model simulates various economic situations and to illustrate the diverse types of analyses produced. Special attention is given to the techniques used to minimize data handling, edit the input data, maintain a historical library of case results, and generate various types of reports.

An automated technique devised to provide plots from data retained within the historical files is also reviewed.

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INTRODUCTION

The Atomic Energy Commission has three gaseous diffusion plants in operation, which initially cost more than \$2.3 billion. The principal service of these facilities is modification of the abundance of the ^{235}U isotope in uranium. Various enrichments of uranium-235 are used as fuels in nuclear-fission reactors of the types currently considered most prominently as prime sources of electric energy. The recent dramatic changes in nuclear power economics and the increases in orders for new nuclear generating plants have caused the Atomic Energy Commission to revise its long-range forecast for the third time in four years. Its current median estimates predict that installed nuclear generating capacity will soar to 8.5 times the present level by 1970, to almost 34 times by 1975, and to more than 81 times by 1980, while the growth of nuclear electric power abroad will be even faster. These potential demands suggest that additional isotope separation capacity must eventually be considered if these growth patterns continue. Furthermore, past experience has shown that approximately four years are required to discover and identify new deposits of natural uranium which are of economic significance. In addition, approximately four years are required to develop newly discovered deposits, construct underground and surface plants, and achieve efficient, full-scale production [1]*.

These considerations represent major problems concerning the most effective future operating plans for the system. In order to produce a more effective mode of analysis for this complex economic system, a mathematical model has been formulated. This model simulates the performance of the production system within this dynamic environment. The primary objective of this effort was to provide a logical basis for: (1) formulating a fundamental policy framework, in which individual policies could be evaluated in relation to each other, and (2) determining whether these alternative policies would be compatible with, and reflect, overall objectives. Although the basic mathematical programming technique utilized in this endeavor was dynamic programming, we have deviated from the traditional systems approach, in which one is primarily concerned with the impact of a decision within one enterprise or one economic domain. Instead we have applied this familiar technique, along with several other innovations, to the integrated or total-system concept. Since these results have been so rewarding, and the approach is so general, we endorse these techniques for the analysis of other production systems.

* Numbers in [] refer to references on page 40.

BASIS FOR THE MODEL

This model reflects a relatively new approach to problem-solving over a span of the business enterprise which has not been subjected previously to significant modeling activities. Specifically, we have applied the total-system concept to facilitate the decision-making process in an area which could be classified as general business problems. Clearly, most problems in the general business climate are not fully controllable or even well-defined; nevertheless, the lack of proper attention to these problems can be consequential. For this reason, we have addressed ourselves to the design and implementation of a methodology which will provide for a systematic analysis within this environment. Before the specific techniques are reviewed, there is merit in elaborating on some of the underlying principles which served as a basis for this endeavor.

Specifically, an attempt has been made to standardize the units and the methodology required to evaluate proposed situations. In so doing, a formal procedure has been established whereby specific proposals submitted by all levels of management can be evaluated on a consistent basis. This action has allowed for a more thorough analysis and hence more alternatives from which to choose. An attempt has been made to design the algorithm by the open-ended concept, which implies that the algorithm primarily consists of discrete units linked together in a logical sequence. This form facilitates modifications within individual units and allows for growth in depth and breadth as the model's validity is established and its uses are increased.

Particular attention has been given to the feedback from higher levels of management. This feedback is usually reflected in the request for more information, which takes the form of "what if" questions. To answer questions of this type, it is usually necessary to alter or vary one or more of the basic assumptions or premises while holding other specified parameters at prescribed values. Requests of this nature are handled by one of two procedures. First, an input case tape is maintained. Therefore, it is only necessary to supply changes in input data to the program. This eliminates a significant amount of data handling and reduces the probability of human input errors. Second, there are numerous options for program control. Perhaps the most versatile of these options is the relative ease with which certain specified parameters can be pre-set. When these parameters are supplied, they are used in the calculations; otherwise, they are determined within the program.

The role of program control options in this model is more substantial than merely facilitating these queries from higher levels of management. It is necessary to be in a position to evaluate particular policies in

relation to the current overall objectives; however, this is not sufficient. Ideally, we would like to be in a position to measure the effects of potential changes in our overall objectives, for they are also subjected to various interpretations. In order to evaluate these consequences, provisions have been made to consider deviations from the current overall objectives. These options do not represent a consensus or even the most likely deviations. Rather, at this stage of development, they represent anticipated options, selected by the model designers, which were mechanically easier to insert into the algorithm in order to reflect additional flexibility.

A difficulty in constructing a model of this nature is the definition and standardization of the information required to evaluate proposals before they are submitted. Consequently, this was not attempted. Instead, the output generated by this program represents an aggregate of the information requested by those having use for the model. Furthermore, the information is in the form which most closely approximates the units which the users are accustomed to seeing in their routine activities. For this reason, there are options as to the type of output desired, although all results are calculated and stored in a library, should they be requested at a later date.

Effective use of this library has proven to be of considerable utility. Technically, the library is a data bank which can be linked to an open-ended report generator and plotting package via an information retrieval system. All cases put into the library are catalogued with the case descriptions. Provisions have been made to allow for changes within the library. The library was designed to serve two functions. It is possible to display summarized results of a series of cases in numerous modes by merely supplying a report option card. Additional calculations may be made at this time. The report generator is open-ended in that it is a relatively simple task to insert or delete individual report generators in this section of the model. Basically, this mode of operation allows the user to analyze a situation in the units to which he is accustomed and still be able to present the results in the units more familiar to his audience.

The second function of the library is to facilitate system analysis on a more comprehensive basis and make the necessary transformations on certain prescribed data sets so that the data will be compatible with other requirements. Sometimes it is possible to use results of previously run cases to analyze new situations, as opposed to defining a completely new set of cases to analyze the particular situation.

In essence, this model provides a mechanism, for anyone who has identified a possible problem or opportunity, whereby it is feasible to analyze the situation, to define more accurately the nature of the situation, and to report the findings effectively in a timely manner. Furthermore,

it allows possible alternatives submitted by others to be evaluated and reported on the same basis. Finally, it provides a natural means for the assemblage of information that may be used to evaluate more encompassing situations.

Before the techniques utilized in this model are described, we shall attempt to define what is meant by the total-system approach to a selected problem area, and to distinguish between the total-system approach and the problem-oriented approach to systems analysis. Also, we shall give a cursory description of our selected problem area as well as the initial representation of this problem area within the model.

TOTAL-SYSTEM CONCEPT

A system may be defined as a complex of entities forming a functional unit within a selected problem area. There are at least two methods for conducting an analysis of any system. First, the entities forming the functional unit may be separated. Usually they are subdivided in such a manner that the ensuing problems can be classified as to form (i.e., assignment, distribution, product mix, inventory, queueing, etc.). The major factor in effective systems analysis is the proper ordering of the relative importance of each of these problems. Since resources are generally limited, one must be selective in picking the most appropriate problems to solve in order to obtain the best description of the system for the stated conditions. In so doing, we generally ask, "Have I solved the right problem? Have I identified all the significant interactions in order to evaluate their combined impact on performance as a whole?" This is the traditional problem-oriented, action-level approach. The second, and more complex method of looking at a system within a selected problem area is to avoid subdivision of the problem universe. All discussions involving the total-system concept focus on this theme. This is a nebulous area, especially with business systems where there are many problems not yet in focus, not yet in control, and not yet understood well enough to be quantitatively described. The basic questions here are, "What is the system? How can this totality be accurately represented?" To find the answers to these two fundamental questions, we must identify the basic restrictions applicable to the total-system concept within the business climate. They may be described as follows:

- (a) Administrative considerations (rather than natural boundaries) almost invariably define the limits to a system.
- (b) In working with a selected problem universe composed of numerous possible subdivisions, the most difficult task is to devise a meaningful set of unambiguous and commensurate units. Hence, when the scope of the system is increased,

the attempt to identify and maintain these meaningful, compatible, standard units introduces complications of a technological and organizational nature. These reasons further tend to limit the description of the system in question.

Each of these approaches to system analysis has its relative advantages. Generally, the more subproblem solutions required to depict a stated system condition, the more desirable is the total-system approach. When attempting system analysis of a business system, there is another major consideration. Within the business organization the basic goals of various groups are logically inconsistent and one is usually satisfied at the expense of the other. As a consequence, these specific goals cannot be completely satisfied simultaneously; e.g., the customers and consequently the sales department desire specific tailoring of product specifications and delivery time to individual needs, while the production department promotes product standardization and delivery times consistent with production smoothing.

Recognizing the limitations associated with the total-systems concept, and the nebulous nature of our selected problem area, we have attempted to construct a mode of analysis within a theoretical framework. Our premise is that a consistent logical approach to the description and consequent analysis of the system will produce more accurate descriptions of the internal interactions. Also, this approach should aid in obtaining a greater insight into the potential effects of various factors outside the control of the system but still influencing its effectiveness. This action should ultimately lead to a more comprehensive systems analysis, a definition of the true problems, and a procedure for providing the right information to the right people at the right time in order that more alternatives may be available for consideration before a specific course of action is selected.

SELECTED PROBLEM AREA

Basically, this problem area consists of acquiring the necessary resources and manufacturing the products, for which there is a scheduled demand, in the most economical manner. Since our stated objective was to provide a logical basis for formulating a fundamental policy framework in which individual policies could be evaluated, it was necessary to strive for maximum flexibility in the model of this particular problem area. With this in mind, it is apparent that it was an inability to derive a more meaningful set of compatible standard units which has, to date, limited the scope of the study of the system in question.

Essentially, this attempt represents an initial "best approximation" of this particular problem area. Experience in manipulating this model has yielded a clearer perspective of the interactions, as well as a better understanding of the parameters involved. This, in turn, has allowed us to establish a natural feedback mechanism by which more meaningful relationships can be inserted into the model. Thus, the scope of the problem area can eventually be expanded or modified without changing the general approach for achieving the stated objectives.

Our initial selected problem area is depicted in Figure 1. It is characterized by three natural components--the market, the production facilities, and the materials management. Current representation of each of these components within the model will now be described. Again, we must emphasize the fact that this is an initial description of a selected problem area. It is described in such a manner that it is possible to study the internal and some of the external interactions associated with the selected problem area on a consistent basis. The hypothesis is that this methodology will provide management with more alternatives to be considered in the decision-making process.

A. Acquisition and Utilization of Raw Materials

There are three sources of raw material for these production facilities--the mining industry, with which the AEC is engaged in long-term contracts; existing stockpiles, composed of various chemical forms and concentrations; and the customer (utility operator) who buys natural uranium ore on the open market and sends it to the diffusion plants to be enriched to the desired uranium-235 concentration. The material from these sources is divided into five nominal classifications: enriched UO_3 , depleted UO_3 , natural U_3O_8 , natural UF_6 , and depleted UF_6 . Each of the UO_3 classifications contains five categories of arbitrary ^{235}U isotopic abundance. The natural U_3O_8 and the natural UF_6 each consist of one category, while the depleted UF_6 may contain as many as fifty categories.

No effort has been made to install a mechanism for determining an optimum feed schedule. Parametric techniques must be used to gain additional insight into this sub-area should the occasion demand such analysis. However, the feed material classifications have been identified for many years, their relative merits have been reasonably well-defined and there is no reason to suspect that these relationships will change significantly in the future. The order of usage for these major classifications of feed is predetermined for each year of a case. Within each classification, the highest isotopic concentration is fed first. It is possible to treat all feed material, other than natural feed, as equivalent tons of natural feed by utilizing the value

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Side Conditions for Physical System

1. Time Period ≤ 35 years
2. Feed Enrichment Categories ≤ 5 concentrations
3. Feed Depleted Category ≤ 50 concentrations
4. Plant Descriptions ≤ 10 per site
5. Plant Improvement Factors ≤ 35 per site
6. Power Constraints ≤ 35 per site

FIGURE 1

function concept.* However, the appropriate conversion charges must be considered when the oxide material is used. An iterative technique has been devised within the dynamic programming algorithm whereby the value of the present inventories, or the marginal cost of feed material used from the existing stockpiles, can be calculated. This value is based on the world market price of feed material in the year all stockpiles are depleted, discounted to the year the feed material is actually used. Should these stockpiles not be depleted, the cost of feed material used from this source is discounted from the last year of the study.

A possible economic situation in the sub-area of raw material acquisition and utilization is one in which the mining industry may not be able to keep pace with the growing demand for feed material. Conceivably, material from the stockpiles could then be offered to prospective customers at a stated price. A mechanism is embedded in the model to evaluate these consequences for various prescribed conditions.

Another possible economic condition to be evaluated occurs when a utility operator is able to purchase feed on the open market and asks the diffusion plant operator to enrich it for him. There is also some probability that all classes of customers will not obtain their feed material on the same feed price schedule; therefore, four other feed price schedules have been provided in order to evaluate the economics of these situations. A feed price schedule is defined as a forecast of the feed costs to a class of customers. We have inserted these schedules in order to distinguish between the cost and demand for feed material. Additional flexibility has been incorporated into the model by having the option that a customer class may purchase a stated fraction of its feed material from two different price schedules. Finally, a separate feed price schedule may be used by the diffusion plant operators.

In summary, the model is designed to handle as many as six different feed price schedules in a given case, although it is acceptable to utilize only one.

B. Market

The market is characterized by a forecast of demand consisting of yearly quantities for tons of uranium, corresponding tons of uranium-235, and tons of separative work** for four customer classifications.

* Several of the basic principles pertaining to isotope separation which have been applied in this effort are discussed in Appendix A - Theory of Isotope Separation.

** The descriptor "tons of separative work" is the term most frequently used to describe one characteristic of the demand schedule. Within this context, it should be considered only as a convenience in nomenclature to describe a certain attribute.

Separative work is the service performed by the production facilities. The measure of separative work is used to describe the energy input required to separate a stated amount and concentration of uranium-235 from a given quantity of feed, which is primarily a mixture of uranium-235 and uranium-238. Naturally, only one demand schedule is required for a given case study; however, there are situations in which it is desirable to distinguish between types of customers.

A basic marketing situation for any customer type may be considered as one in which the customer does not supply feed material to the diffusion plants. Therefore, his only interaction with the diffusion plant operator is the purchase of a given amount of uranium-235. Essentially, this is the present marketing condition. However, in the future, if the customer is allowed to supply his own feed material and purchase a specified quantity of separative work, the marketing picture will become increasingly complex. Additional complexities arise if the waste material (the effluent depleted in the uranium-235 isotope) resulting from a given order should be returned to the customer. This waste material may have intrinsic value either to the customer or to the diffusion plant operators. The value to the customer arises from the fact that he may have other uses for this material. The value to the diffusion plant operators, and indirectly to the customers, results from the fact that in the future it may have value as feed material for further extraction of ^{235}U if the cost of feed should increase significantly.

With this in mind, the following alternative yearly marketing representations have been implemented independently for each customer classification. Here there are only two primary situations; however, each of these situations leads to various other qualified conditions.

1. Waste material not returned to the customer.
 - (a) Feed material is not supplied by the customer.
 - (b) A portion of feed material is supplied by the customer.
 - (i) The quantity of feed actually required is determined by diffusion plant's waste concentration.
 - (ii) The quantity of feed actually required is determined by the customer's waste concentration specification.
2. Waste material returned to the customer.
 - (a) The quantity of feed actually required and the concentration of the waste material returned are determined by the diffusion plant's waste concentration.
 - (b) The quantity of feed actually required and the concentration of the waste material returned are determined by the customer's waste concentration specification.
 - (c) The quantity of feed actually supplied is determined by the customer's waste concentration specification, and the concentration of the waste material returned is determined by the diffusion plant's waste concentration.

C. Production Facilities

The production facilities consist currently of three physical plants located several hundred miles apart. Despite their geographical separation, they are operated as an integral system. There is a provision in the model to incorporate the description of a new plant. Therefore, the production complex as reflected in the model may contain as many as four plants.

The plant performance relationships (separative capacity versus required power) are input to this model. Each plant may be modified on a yearly basis by multiplying these relationships by some factor different from 1.0, as illustrated by Figure 2. This is a relatively easy method for postulating plant improvement programs or plant performance deteriorations with time. Also, this procedure minimizes data handling and reduces the probability of error. There is an additional provision by which as many as ten different performance descriptions per plant can be used throughout a given campaign. This provision is only utilized whenever the desired changes in operating characteristics cannot be obtained with the technique just described.

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Where: Separative Capacity = (Function of Power) k

FIGURE 2

When capital improvement programs are being considered, they must be evaluated by comparing individual cases; however, the algorithm will optimize the time at which the new plant should be brought onstream. This is accomplished by allowing it to be integrated into the system when the incremental cost of product in the old system (without the new plant) would otherwise exceed the stated incremental cost of product for the new system (augmented by addition of the new plant).

In addition to capital improvement considerations, the model is used to determine long-range production schedules. These schedules are of particular importance in this system since there exist two major cost components--feed material and power. Both of these resources are acquired through long-range contracts; scheduling changes within these contract periods will usually result in some form of economic penalty and funding commitments are required years in advance of actual implementation.

Several other costs considered in this system are startup, shutdown, and standby costs. These cost concepts, as expressed in this model, may be slightly more inclusive than one usually infers from these terms. This is due to the fact that we are constantly making every effort to adhere to the "ideal cascade" principle throughout all operations (See Appendix A). These cost data also include the costs associated with adding or removing various units within a given plant, depending upon the particular demand schedule in question, in order to approximate ideal conditions.

The other cost factors considered are operation, depreciation, overhead, and miscellaneous costs.

BASIC ALGORITHM

A particular situation of interest is translated into input for this model by the selection of the appropriate parameters for the problem area just described. Specific examples of some of these parameters are the market profile, the appropriate capital budgeting program, a particular materials management description, and a designated cost of power schedule. The objective of the dynamic programming algorithm is to determine the optimum operating strategy over a period of time for these prescribed conditions.

Before describing the mechanics of this algorithm, there are several considerations which should be discussed. For the production facilities, the marginal cost of product versus production is monotonically increasing. This is assured by the characteristics of the major cost components and the inherent design criteria which allow, within limits,

the ability to adjust plant size in order to approximate the ideal cascade.* Also, for any optimum strategy, the cumulative demand for the campaign must be exactly satisfied; and the cumulative production must always equal or exceed the cumulative demand throughout the campaign. These facts permit the formulation of a straightforward method for determining an optimum operating strategy.

A necessary condition for the optimum non-constrained operating strategy is that the discounted incremental cost of product be constant throughout the campaign. Basically, this allows for pre-production, and permits production at minimum cost. Of course, the appropriate carrying charges are considered, and the present-value concept is utilized. Additional insight into this concept may be obtained from Figures 3A and 3B, which have identical time periods.

FIGURE 3A

* The fact that the marginal cost of production is monotonically increasing with production does not restrict this methodology. It may be extended to the more general situation where the unit cost of product versus production has a stationary point. This is the situation which will occur more frequently, as plant capacities are usually more rigid.

FIGURE 3B

The equal discounted incremental cost of product (EDIC), curve X, yields an optimum operating strategy, curve B. This strategy satisfies any cumulative product demand schedule which (1) passes through point b and (2) contains sub-period cumulative product demands which lie within the region encompassed by curve B. However, there are demand schedules which do not fulfill these criteria. See Curve C at years L and M. For those years the cumulative product demands fall outside the area under curve B. The EDIC concept is not adequate because the cumulative demand schedules for various sub-periods have not been satisfied. Nevertheless, we are now in a position to state the sufficient conditions to satisfy our stated optimum operating strategy. After establishing curve B, we continue by considering the smallest sub-period, 0 to L, in which the constraints are not satisfied. We apply the EDIC concept to this sub-period and satisfy exactly the cumulative demand. Observe, from curve Y, that it is necessary to increase the incremental cost of product in order to accomplish this. Next we consider the sub-period, L+1 to N, and exactly satisfy its cumulative demand schedule by utilizing the EDIC concept. Here, the incremental cost of production will be lower than in sub-period 0 to L. After determining the optimum mode for period L+1 to N, we check its sub-periods for violations of the cumulative demand schedules within this period. We continue forward in this manner until all sub-period constraints are satisfied. This

action yields curve Y , which permits us to describe the optimum operating strategy which satisfies the aforementioned requirements.

This procedure may be stated more formally as follows:

For $1, 2, \dots, i < N$ sub-periods,

then $(EDIC)_1 \geq (EDIC)_2 \geq \dots \geq (EDIC)_i$,

subject to $(\sum P)_1 = (\sum P)_2 = \dots = (\sum P)_i = 0$,

when $(EDIC)_1 > (EDIC)_2 > \dots > (EDIC)_i$,

where $\sum P \equiv$ amount of pre-production in the sub-period.

The procedure just described is one of the stages of the dynamic programming algorithm. We have designated this stage as "the iteration on incremental cost of product."

We are now in a position to give a formal description of this basic algorithm. (It is not within the scope of this report to describe the concepts of dynamic programming. A lucid description along with more detailed references, can be found in Management Science [2].)

The dynamic programming stages are:

1. Iteration on initial year of new plant.
2. Iteration on incremental cost of product.
3. Iteration on cascade waste material concentration.

The dynamic programming states are:

1. Any year in the campaign.
2. Any incremental cost of product greater than zero.
3. Any waste concentration between zero and the natural feed concentration.

The solution technique is initiated by assuming a year the new plant is to be brought onstream. (If new plant studies are not being considered, the algorithm consists of only two stages.) Also, an initial incremental cost of product is assumed. These data, along with the previously stated input parameters, supply sufficient information to quantify the optimum operating configuration for these stated conditions, via the

"iteration on cascade waste material concentration" stage.* We proceed by modifying the incremental cost of product in the manner previously described. Each time it is changed, it is necessary to re-optimize the operating configurations by means of the "iteration on cascade waste material concentration" stage.

The final consideration is the description of the "iteration on initial year of new plant" stage. Its function is to determine the optimum time for bringing a new plant into the existing configuration. One should not lose sight of the fact that every change described during this stage involves satisfying all of the previously stated criteria pertaining to the profile of incremental cost of product throughout the campaign.

For the purposes of illustration, we shall assume that our original estimate for the new plant to come onstream was year N , the last year of the campaign. At this point in the calculation, we have the condition represented by the optimum production schedule, curve A in Figure 4A, and the discounted incremental cost of product profile, represented by curve A' in Figure 4B.

FIGURE 4A

* We will not describe this stage in detail because it is essentially problem-dependent. The primary function of this stage is to describe the optimum operating conditions for the prescribed conditions. Additional insight into how this is obtained for this particular problem may be obtained from Appendix A.

FIGURE 4B

We compare the incremental cost of the new plant, as expressed by a previously determined schedule which is one of the input parameters, with the final EDIC number for the present configuration. If the new plant cost level is higher than the corresponding existing configuration cost level, the new plant is not brought into the system and the calculation is complete. Should the new plant cost be lower, we decrease the campaign by one year and calculate the optimum production schedule for this new campaign period. Again, we compare the appropriate new plant cost level with the associated EDIC number. (See curve B' in Figure 4B.) This procedure is repeated until the EDIC number for the present production complex for the last sub-period is lower than the corresponding new plant incremental cost. Suppose this occurs for a campaign length of years 1 through M-1. This infers that the campaign has been decreased by a total of N-(M-1) years. (See curve C' in Figure 4B.) The new plant is then added to the configuration in year M. Should the original estimate have been something other than the last year of the campaign, the same comparisons are made; however, if the new plant's incremental cost of product was higher than that of the present facilities on the first comparison, the procedure would be reversed and the sub-period campaigns would be increased instead of shortened. With this procedure we would attempt

to determine the first year in which the appropriate value for the existing configuration would exceed its new plant counterpart. This particular algorithm is further complicated by the fact that not all of the required information is available to complete the second stage calculations. This situation arises because of the possible interactions between the customer action and the material management aspects of this problem area. A specific problem arose when we attempted to modify the present-value concept in order to establish the value of the existing stockpiles. As described previously, the marginal cost of the feed material in the stockpiles is to be discounted from the year in which all stockpiles are depleted to the year in which the feed material is actually used. Obviously, the year in which the stockpiles will become depleted is not known prior to the study. For this reason we have imbedded within this algorithm an additional iteration procedure, between stages 1 and 2, to determine this year.

CASE OUTPUT

There are more than 200 items calculated on a yearly basis for the campaign. This information requires 12 to 30 pages of output, depending upon the length of the campaign and the various output options employed. An example of this output is found in Appendix B. This example contains the least amount of information required to demonstrate all of the features involved.

All of these output items are not considered as decision variables. In fact a considerable quantity of these data contains similar information in slightly different forms. For example, a substantial amount of the cost data appears with and without interest as well as on an annual and cumulative basis. However, one of the stated objectives was to provide appropriate information for each user of the model. It is this desire for versatility which is reflected in this output.

The case output is divided into six major sections:

1. Input - This information is always printed for each case in order to record the data actually used for the calculations.
 - (a) Case description - This is a narrative description of the more pertinent parameters.
 - (b) General information - This is all data which do not fall into any specific category.
 - (c) Marketing information.
 - (d) Material management information.
 - (e) Description of production facilities.
2. Case Summary - This information is optional and depicts the yearly values of the major cost components; it also shows the annual levels of operation for each of the plants.

3. Feed Detail - This information is optional. Here the costs, and the type and quantities of feed material received, fed, and sold, are reflected.
4. Customer Feed Detail - This is an optional report reflecting the cost and amount of feed each customer purchased.
5. Net Cash Flow - This information is optional and shows the cash flow analysis.
6. Discounted Cost Summary - This is an optional, detailed summary report on the cash flow and costs for the government, customer, mining industry, and "total enterprise" on an annual and cumulative basis.

FUNCTIONAL ORGANIZATION OF THE MODEL

The previously stated primary objective was to provide a logical basis for formulating a basic policy framework. This framework could be used, in turn, to evaluate alternative policies in relation to each other, and to determine whether these policies are compatible with, and reflect, overall objectives. In order to achieve this objective, it is necessary to distinguish between two polar types of decisions. One class of decisions are non-programmable to the extent that they are novel, unstructured, but consequential. By definition, this class of decisions must be dealt with outside the computer. The other class of decisions are programmable to the extent that they are repetitive, and a rational procedure can be described for handling them. The model developed has been designed to cope with this second class of decisions in the selected problem area. In addition, we have considered the interactions between the two classes of decisions. The most obvious interaction arises when certain types of programmed information are required to support a non-programmable decision. This need may be translated into a request for a series of new cases, a request to search for and retrieve information from the library of previous cases, or perhaps even to transform certain data into a more meaningful form or into some new combination. Once a particular request has been established, there are other interactions for obtaining, in the most effective manner, the needed information. Figure 5 depicts the functional organization structure developed within the program in an attempt to accomplish these tasks.

FIGURE 5

The major functional responsibilities of the individual programs contained within this organization structure can be summarized as follows:

1. SUPV - All requests for data are made through this program. Program control is regulated here. If the scheduled request cannot be adequately filled, SUPV takes appropriate action such as skipping to the next case, or preparing a case for restart if optimization of a case is interrupted due to excessive computing time requirements. Restart may be defined as continuing the calculations from that point of the computations at which they were interrupted, should the checks indicate that the program control has not been impaired. By means of SUPV, periodic progress reports are issued via the on-line printer. Program modification from the operator is accepted through various sense switch operations. For example, should the periodic progress reports indicate an error, it is possible to "debug" the appropriate section before taking further action.
2. MAIN 1 - The primary functions of this section are to ensure that each case is completely and correctly defined in order to minimize the amount of data required for a series of cases, and to eliminate the possibility of improper sequencing within a case. The first task for this section is to sort all the data associated with the case in question. Essentially, these data are separated into categories similar to those previously discussed. (See the description of the reporting features associated with the input parameters in the Case Output Section.) Furthermore, these data are sorted in greater detail in this program sector.

One of two possible alternatives in processing the input data is that either the case tape does not exist, or it does exist but must be completely revised. (A case tape is one which contains all of the data, in their designated positions, required to complete a case study.) For this first alternative, it is necessary to supply a large portion of the data required to complete a case. There is a high probability that numerous yearly parameters will be held at a fixed value for some portion of the study, if not for the entire campaign. For data in which this is likely to occur, it is only necessary to supply an initial value. This number is placed in the appropriate positions until a similar card with a designated

change is received. This action is of consequence when one considers that a case may cover a 35-year span. It is also necessary to edit these data to minimize the probability of using improper data for computer calculations which may require several hours on a high-speed computer to complete. These editing features attempt to recognize two distinct classes of errors: (1) those which represent data which have been incorrectly transposed, and (2) those which represent omissions of required data. When a transposition error occurs, the card type, the error type, and the card image are stored. After all data are verified, the card type and card image are displayed for each error. At this point a check is made for missing data. A list of missing data is displayed. Naturally, the discovery of any error will prevent the case from being processed. However, the editing cycle is completed to assure detection of all errors in one scan.

The second possible alternative in processing the input data arises for the situation in which the case tape exists prior to the processing of a given case, but where the user would like to modify it before running the case. In this situation the editing aspects are slightly modified. The checks for the first class of errors are the same; however, only the modifying data are considered. Since modifications are being made to the case tape, one is no longer concerned with deletion errors. However, the existence of a case tape introduces another potential class of errors--that of association. By this we mean that there are certain consequential associations within specific data classifications and these data may be meaningless unless considered together. At this stage, error checks are made for compatibility of the data. Again, any detection of errors in the data will prevent the processing of the case.

Another function performed in this section is the recording of input parameters onto the case output tape. The final function to be considered is that of maintaining the output options and error considerations for each case in the sequence. The purpose of this function is to generate the data required to conform to the documentary standards for classified material.

3. MAIN 2 - This section contains the dynamic programming algorithm previously described.
4. MAIN 3 - All computations appearing in the program output, but not required for optimization in MAIN 2, are made in this section. After these calculations are completed, the output is written on a program tape which contains only the cases for a particular sequence.
5. MAIN 4 - When all cases are completed, a document which adheres to the security classification standards must be prepared.

This task is done by this section. In addition, abstracts of each case description are prepared in order to maintain a file describing the cases in the case library. This section also performs a series of calculations which are used in another program involving the USAEC reactor complex.

There is a certain amount of internal bookkeeping which must be handled in this section in order to determine the number of pages, and the sequence in which the output is to appear in the final report. For example, there can be two variable dimensions which will determine the number of pages in each report--time, and the number of cases. The time variable is usually displayed across the page, and the variables of interest and parameters are usually displayed down the page. (See sample output in Appendix B). When it is not possible to display all information on one page, the time variable is extended first; thus the same variables for the extended time period will appear on the second page. Should it become necessary to extend the output format in the other dimension, the third page would contain the additional variables for the first time period and the fourth page will contain similar data for these same variables during the extended time period.

6. MAIN 5 - There is an option in the program which allows a sequence of cases to be added to the library tapes. If this option is exercised, these efforts are performed in this program. The present library contains results of several hundred cases stored on a series of tapes. It is the further function of this section to determine whether any cases are to be added to the library, or whether certain cases are designated to replace older cases. Upon determination of this question, the appropriate action is taken.
7. MAIN 6 - The basic function of this section is to supply plots and special reports consisting of selected data from within the last sequence of cases, the library tapes, or a combination thereof. Both the plotting package and the report generators are "open-ended" and possess variable structure characteristics. Although the underlying operational aspects for both of these features are similar, their composition will be discussed separately. Essentially, the similar operational characteristics of these features parallel those of an information retrieval problem.
 - (a) Plotting Package: The basic function of this package is to provide any plot desired. In order to accomplish this task we must be able to construct plots from among any of the cases on the library tapes, as well as from parameters within a given case. Thus, the option of designating the abscissa and ordinate parameters exists. It is possible to select up to seven variables as ordinate parameters for the same plot.

Of fundamental importance in this endeavor is the ability to retrieve any variable stored on the library tapes. In order to do this, two pieces of information are required: the case number and the parameter involved. For this package, 60 parameters have been designated, within a case, as potential plotting candidates.* In so doing, the criteria for retrieving any desired information in the library have been fulfilled.

These plots may be obtained independently of the generation of specific cases. In order to acquire a plot, the following card is utilized.

D1	D2	D3	D4	P1	P2	P3	P4	P5	P6	P7
----	----	----	----	----	----	----	----	----	----	----

where:

- D1 - distinguishes between a line and a bar plot,
- D2 - designates the abscissa parameter (if D2 is blank, years are used for this parameter),
- D3 - designates the case within which various parameters will be plotted (a blank indicates a plot of one specified parameter among cases),
- D4 - specifies the parameter to be plotted among the designated cases (a blank indicates a plot of various parameters within a case),
- P1 . . . P7 - contain the ordinate variables which will either be case numbers, or line items within a particular case.

A sample of plotting within a case is represented in Figure 6, while an example of plotting among cases is shown in Figure 7. Of particular importance is the fact that this section of the program selects the optimum scaling factors for each plot, and automatically writes the appropriate labels. The approximate size of the actual plots is 12 inches by 18 inches.

- (b) Report Package: This package, which is not completely operational at this time, fulfills three objectives. First, it provides summary reports depicting comparisons of only the more significant parameters within a sequence or with similar data from the library. Second, it provides the mechanism for making special, less routine,

* This was a rather arbitrary decision and can be readily expanded, should future usage indicate that this original selection was not adequate.

FIGURE 6

FIGURE 7

calculations on a large reservoir of data without going through the expensive and time-consuming process of collecting and translating these data into a form which is amenable to computer usage, or without disrupting the main program control system. Third, it provides the data necessary to study the correlations among the interactions within the system. Ultimately this should lead to more effective parametric analysis and more accurate, and less cumbersome, system descriptions. This in turn will allow the selected problem area to be expanded or described in greater detail.

Each report generator in this package has a particular function. It may be to display specified parameters in a different format, and/or it may make detailed calculations on data, all of which may not be available at the time a specific situation is being evaluated. This package is "open-ended" to the extent that procedures may be added to or deleted from the package with relative ease. As the maximum utilization of available data.

The general structure of a report from this section is shown in Figure 8. The Output Descriptors may be the particular parameters involved in a summary report or they may exhibit the results of calculations performed by this sub-program. Basically, they depict the reporting function of the particular sub-program in question. It is quite possible that these Output Descriptors will not always be adequate to describe the particular analysis to a person not intimately involved with all aspects of the existing situation. In particular, this occurs when preparing reports for special interest groups or reporting less routine results computed from the available information on the library tapes. For these situations, provisions have been made for supplementing the basic Output Descriptions. These supplements appear in the form of Header, Sub-Header, and Footnote Descriptors which may be included at the time the reports are needed. However, the presence of these descriptors is not required.

The major limitation in using the present report package is that only one of each type of report may be obtained on a given run.* To use the package, it is necessary to input any Header, Sub-Header, and Footnote Descriptors which will be needed for any of the reports. Another requisite is to submit a series of the following control cards.

* This is a minor limitation from the implementation point of view. The limitation stemmed more from practical considerations at this point in time.

FIGURE 8

Table	Header	Sub-Header	Footnote	Cases
-------	--------	------------	----------	-------

These control cards are sorted such that cases are ordered within sub-headers, sub-headers are ordered within headers, and finally headers are ordered within tables. It is the table numbers which determine which calculations should be made. The pagination versatility described under MAIN 4 is also available in this reporting function. Information from multiple cases is handled in the same manner used for variables.

Tables 1, 2, 3, on pages 41, 42, 43, respectively, are examples of the type of output which can be generated in this section.

SUMMARY

There are several general observations pertinent to the design and implementation of the total-systems concept that are worth noting. The criteria for success with the total-system approach, as contrasted with the more familiar engineering-system methodology, are somewhat different. Success with the total-system concept is dependent upon recognition of these differences at a very early stage of the project. From the engineering-system viewpoint, this project may be seen as a task of designing and implementing a practical computer program that would apply a fairly complex type of calculation to a very large-scale problem. This task would probably be divided into three stages: problem formulation, model building, and implementation. Each stage would be completed before the next one was begun. From the total-systems viewpoint, this procedure is not possible. There can be no complete isolation of these stages because there are no standard techniques, the guide lines of behavior are more nebulous, and/or information may not be readily available. The methodology needs to be tested and, in part, developed, in a realistic setting. Also, when considering the total-system concept, more emphasis must be placed on communication of ideas, the theory involved and interpretation of results to many individuals with diverse backgrounds and organizational responsibilities. With these distinctions in mind, it seems appropriate to discuss a few of the underlying factors which influenced the success of this project.

First - perhaps the most significant factor - is the type of environment in which one is attempting to formulate a problem, develop a technique, and implement a procedure to obtain a general solution. It is frequently necessary to convince a prime user that he, indeed, has a problem. He

must then be persuaded that you have a solution to that problem. In this situation it is difficult to secure the user's interest and support for an effort of this magnitude. Fortunately, this condition did not exist at any time throughout these endeavors. There was never a question of acceptance--only of validity. Too, we were aided by the fact that there was a mechanism in the existing organization which yielded a partial comparison with current performance. Although this mechanism was extended many times, its primary usefulness was in providing a framework within which new concepts could be introduced.

Second, the basic idea involved in total-systems orientation is that the activity of any part of the organization has some effect on the activity of all other parts. In order to evaluate any decision or action, it is necessary to complete the following tasks:

1. Identification of all of the significant interactions, and
2. Evaluation of their combined impact on performance as a whole (and not merely on the part originally involved).

All competent, experienced industrial personnel can complete the first task; however, the second task necessitates expanding and complicating the statement of the problem. This is contrary to the previous training or experience of most managers and scientists, for they are well versed in taking a complex problem and cutting it down to size, isolating it from its environment, and eliminating the aspects which tend to make it difficult to solve. These actions allow them to utilize standard techniques and capitalize on past experience. In recent years, there has been a phenomenal increase in methodologies which may be used to cope with more complex problems. In fact, this rapid growth has essentially created a new discipline. Unfortunately, the practitioners of this new discipline have a tendency to overemphasize techniques which are not fully understood or accepted. Also, they possess too much enthusiasm for the mechanics involved and are somewhat limited in understanding the industrial climate. The success of this project or any similar project is directly dependent upon the ability to fuse the activities of analyst and management into a concerted effort, since neither group can be effective alone. It was this concerted effort by a team possessing the proper balance between experience and the appropriate technical skills which allowed us to proceed toward the successful achievement of the stated goals for total-system analysis.

Third, it is one thing to create a team capable of formulating and constructing a model of a system which closely satisfies a prescribed set of objectives, under an essentially controlled laboratory environment. It is an altogether different task to manage this new tool in order to ensure proper and effective utilization for support of decision-making after it has been satisfactorily scrutinized for validity. Essentially, this is a communication problem. Granted, effective communications are difficult when one is attempting to achieve agreement on common problems, especially where different disciplines are involved.

But one might inquire about the additions or modifications to the existing communication channels which result from the many users of a model incorporating the total-systems concept. Certainly there will be numerous users because a mechanism for evaluating significant interactions within the system which have not been measured previously will attract the attention of all interests responsible for the segments involved. How does one inform these various users of the various options which are available for use in formulating their specific problems more effectively? Furthermore, how does one inform them of what is already available for their analysis? Basically, these users must develop an early technical understanding of the solution forms and techniques. This imposes a burden on the team creating the model that they may not be willing to bear. It is one thing to score breakthroughs, and it is another to suffer the frustrations of trying to convey the information resulting from the solution techniques to a new user who has a different set of values and frame of reference. These communications must be achieved, and this achievement comes only after the broad concepts are mutually accepted and understood. However, this task becomes much easier as success accumulates. The important factor here is that these potential users must be identified and kept informed of the status and progress throughout all activities.

In summary, it is now possible to propose a three-phase procedure for coping with the total-system concept which has proven effective on this project.

First, the technological gap must be closed. The theoretical attractiveness of most new concepts is well ahead of our ability to accept the application of them to the decision-making process. Various concepts may be compared while all of the data are being collected and put in the most amenable form. Too, there is a high probability that the main sources of these data will eventually be users of the model. Therefore, it is highly profitable to obtain some insight during this phase as to the primary uses of the resulting information in order to design more effective validity tests and reporting packages, as well as to establish a base for efficient implementation at a later phase of the project. As the potentially more effective concepts appear in the analysis of new technology, they should be introduced to the potential users in a meaningful fashion.

Second, it is necessary to assess the performance under realistic conditions. In an intricate model, there are too many assumptions to permit a simple test of a given hypothesis. It is necessary to emphasize all of the crucial parts of the proposal and to make comparisons with any previous or competing systems. Also, some of the proposed guidelines may be tested or, in part, developed in this phase. There will probably be many studied compromises due

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efforts prior to this model produced approximately 50 simplified cases per year--simplified in relation to the problem area described in this report and in relation to the technology employed.

The practicality of such a model to measure and to determine the significant interactions within the selected problem area is best reflected in the sample of case output as shown in Appendix B (it must be remembered that any particular aspect can be emphasized through the plotting or reporting package.) Also, these data, along with the special reporting features of this model, have facilitated the completion of several non-routine studies which previously could not have been made in toto due to the unavailability of the requisite data in the proper form. These studies were primarily concerned with specific interactions between the uranium separation and reactor production facilities. In fact, a portion of the data required for this analysis is not calculated routinely in this model.

Finally--perhaps the most significant aspect of this project--efforts are being continued in an attempt both to expand the utilization of the results of this total-system analysis and to develop a more sophisticated technology which will extend computational efficiency and versatility.

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2. Howard, Ronald A., "Dynamic Programming." Management Science, January, 1966, Volume 12, Number 5, Page 317.
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4. Benedict, Manson, and Pigford, Thomas H., Nuclear Chemical Engineering. New York, New York: McGraw-Hill, 1957.

TABLE 1

ANNUAL OPERATING BUDGET COSTS* FOR ALTERNATIVE OPERATING SCHEDULES - \$ MILLIONS

<u>Case</u>	<u>FY</u> <u>1812</u>	<u>FY</u> <u>1813</u>	<u>FY</u> <u>1814</u>	<u>FY</u> <u>1815</u>	<u>FY</u> <u>1816</u>	<u>FY</u> <u>1817</u>	<u>FY</u> <u>1818</u>	<u>FY</u> <u>1819</u>	<u>FY</u> <u>1820</u>	<u>FY</u> <u>1821</u>	<u>Cumulative \$MM</u> <u>FY 12-21</u> <u>FY 12 - 27</u>
<u>Low Requirements</u>											
A10											
A12											
A13											
A13A											
A14											
<u>High Requirements</u>											
B10											
B10A											
B20											
B30											

* In \$ Millions and includes out-of-pocket costs for power, Operations and Maintenance, cascade improvement, and shutdown and standby costs.

Case Notes

Case B10A Is a variation of Case B10, to illustrate advantages of an optimized schedule for power additions in the 1820's.
Case A13A Is a variation of Case A13, to illustrate advantages of an optimized schedule for power additions in the 1820's.
Cases B20 and B30 Respectively, represent x-site and y-site operation at the (yyy) MW level for high requirement range.
Cases A12 and A13 Respectively, represent x-site and y-site operation at the (yyy) MW level for low requirement range.
Case A14 Represents x-site operation at (xxx) MW level.

TABLE 2

SUMMARY OF OUT-OF-POCKET FEED* & SEPARATIVE WORK COSTS

Cost to AEC										Customer Feed Cost													
Sep. Work		Conv. UF6		Sub Total		Credits**		Sales		1980	Net Costs		Diff. vs. Cs I		for UF6			Total			Difference		
w/o	I	w/I	w/o	I	w/I	w/o	I	w/I	w/o	I	Inv.	w/o	I	w/I	w/o	I	w/I	w/o	I	w/I	w/o	I	w/I
<u>Low Requirements</u>																							
Low Feed																							
Case A-10																							
A-31																							
A-22																							
A-43																							
A-55																							
A-3A																							
High Feed																							
Case A-10																							
A-31																							
A-22																							
A-55																							
A-3A																							
<u>High Requirements</u>																							
Low Feed																							
Case B-10																							
B-31																							
B-22																							
B-1A																							
High Feed																							
Case B-10																							
B-31																							
B-22																							
B-1A4																							
B-1A5																							

* Does not include expenditures for ore concentrate procurement FY 12-FY 21

** For sales of U₃O₈ and UF₆ from AEC surplus inventories and credits for 1817 uranium inventories

TABLE 3

SUMMARY OF UNIT COST OF SEPARATIVE WORK BY MAJOR COST ELEMENTS

CASE	Low Requirements With U_3O_8 Concentrate					High Requirements With U_3O_8 Concentrate			
	<u>I-5</u>	<u>II-A3</u>	<u>II-B3</u>	<u>III-4</u>	<u>IV-3</u>	<u>I-5</u>	<u>II-A3</u>	<u>II-B3</u>	<u>IV-3</u>
<u>COSTS, \$ MILLIONS</u>									
Cascade									
Depreciation									
Added Factor									
Subtotal									
Interest on Feed For Preproduction For Flywheel									
Total									
<u>UNIT COST OF SEPARATIVE WORK, \$/KG U</u>									
Cascade									
Depreciation									
Added Factor									
Subtotal									
Interest on Feed For Preproduction For Flywheel									
Total									
<u>Separative Work, MTU, used to compute unit cost increments except for flywheel.</u>									
<u>Separative Work, MTU, used to complete flywheel unit cost increment (FY 12-17).</u>									

APPENDIX A

Theory of Isotope Separation

There are several good references pertaining to the separation of uranium isotopes [3,4]. For the purposes of this paper, it is not necessary for one to have a knowledge of all of this material. However, there are several concepts based on this theory which will aid in the understanding of the methodology utilized in this algorithm.

There are three related concepts which warrant description. They are "ideal cascade", "separative work", and "value function". Before these terms can be defined, we need to develop one additional relationship, namely, the mathematical manipulations associated with separation of mixtures with very small separation factors.

Every binary separation mechanism is characterized by a separation factor α which is defined as

$$\alpha = \frac{\frac{Y}{1-Y}}{\frac{X}{1-X}}, \quad (1)$$

where

Y = the concentration of the desired isotope in the enriched stream,

X = the concentration of the desired isotope in the depleted stream.

Another separation factor may be defined as

$$\psi = \alpha - 1. \quad (2)$$

By combining equations (1) and (2) we obtain

$$\psi = \frac{Y-X}{X(1-Y)} \quad (3)$$

Solving for Y:

$$Y = \frac{X(1+\psi)}{1 + \psi X} \quad (4)$$

Subtracting X from both sides:

$$Y-X = \frac{\psi X(1-X)}{1 + \psi X}$$

Since $\psi \ll 1$ (0.0043 for this particular process) and $X < 1$, a binomial expansion of the denominator yields

$$Y-X = \psi X(1-X) (1 - \psi X + \psi^2 X^2 - \dots)$$

Ignoring terms containing ψ raised to a power of two or more, we obtain

$$Y-X \approx \psi X(1-X). \quad (5)$$

Now consider a stage in a cascade processing a two component mixture as in Figure 1.

Figure 1

In this diagram, L is the mass flow per unit time and x is the concentration of the desired isotope in the mixture prior to the increment δx of separation. It can be seen from this figure that

$$Y-X = 2\delta x. \quad (6)$$

Since work has to be done on a feed mixture in a stage to perform a

separation, there is more "value" in the separated form than in the mixed form. Thus, we want to find a "value function" to describe this change. It should have the following properties:

1. If $V(x)$ represents the value of one unit, then $MV(x)$ represents the value of M units.
2. The value increment produced by a stage should be independent of the concentration of the desired isotope.

Assuming the existence of $V(x)$, the value function, a value balance around the stage is made:

$$\Delta U = LV(x+\delta x) + LV(x-\delta x) - 2LV(x), \quad (7)$$

where ΔU = the change of value produced by that stage, (i.e., the separative work). Since the separation per stage is so small (i.e., $\psi \ll 1$),

$$(x+\delta x) \approx x \approx (x-\delta x) = X$$

Expanding $V(x+\delta x)$ and $V(x-\delta x)$ in a Taylor's series about x results in

$$V(x+\delta x) = V(x) + (\delta x) V'(x) + \frac{(\delta x)^2}{2} V''(x) + \dots$$

and

$$V(x-\delta x) = V(x) - (\delta x) V'(x) + \frac{(\delta x)^2}{2} V''(x) - \dots$$

Substituting the first three terms of these expressions into equation (7) we obtain

$$\Delta U = L(\delta x)^2 V''(x). \quad (8)$$

From equations (5) and (6) we can write

$$2\delta x = \psi X(1-X).$$

Substituting this expression into equation (8) we obtain

$$\Delta U = \frac{L\psi^2}{4} [X(1-X)]^2 V''(x). \quad (9)$$

But to make ΔU independent of concentration, let

$$V''(x) = \frac{1}{x^2(1-x)^2}, \text{ where } X \approx x.$$

This ordinary differential equation has the general solution:

$$V(x) = C_0 + C_1 x + (2x-1) \ln \left[\frac{x}{1-x} \right],$$

where C_0 and C_1 are arbitrary constants.

A particularly useful form of $V(x)$ arises if we let

$$V'(.5) = V(.5) = 0.$$

In so doing, we have explicitly defined our "value function" as

$$V(x) = (2x-1) \ln \left[\frac{x}{1-x} \right].$$

If the above equation is accepted as the definition, equation (9) reduces to

$$\Delta U = \frac{L\psi^2}{4}.$$

This expression defines the "separative work" of any stage in a cascade.

In an "ideal cascade", the stages are linked together to form a cascade such that there are no losses of "separative work" anywhere in the cascade. This would be accomplished by not mixing streams unless their concentrations were identical. Although not obvious from this discussion, the "ideal cascade" also maximizes the "separative work" of any stage, and minimizes the stage upflows. In order to build an ideal cascade every stage would be of a different size for a given production rate. Therefore, it is uneconomical to build an ideal cascade; nevertheless, it is

an extremely useful concept since a "squared-off" tapered cascade can be built which closely approximates the ideal cascade.

Methods are available for measuring deviations from ideality. Basically, the plant descriptions used in this program are arrived at through a series of optimizing procedures over the entire range of operating levels. These calculations make use of individual stage properties as determined from test loops and plant test data, as well as the expected theoretical considerations. All of these efforts are conducted outside of this program. The composite results are input to this model. Inherent in these performance characteristics is the mechanism which modifies squared-off cascade calculations to correspond with the ideal considerations (i.e., an isomorphism).

By the definition of the "ideal cascade" it is obvious that the total separative work equals the sum of the separative work of the stages. Furthermore, since an output from one stage is the input to another, all interstage flows cancel in the cascade summation. Hence, for the cascade in Figure 2 one obtains the following important relationship:

$$U_{\text{Total}} = PV(X_p) + WV(X_w) - FV(X_f), \quad (10)$$

where
$$V(x) = (2x-1) \ln \left[\frac{x}{1-x} \right].$$

Figure 2

In this diagram, the symbols are defined as follows:

P = mass units of product,

W = mass units of waste,

F = mass units of feed,

X = concentration of flow stream.

Subscripts p, w, and f refer to flow streams of product, waste, and feed, respectively.

Two other material balance equations are required to complete the productivity equations for this situation:

$$0 = PX_p + WX_w - FX_f \quad (11)$$

$$0 = P + W - F. \quad (12)$$

It may be seen as a logical generalization of equations (10), (11), and (12), and the definition of an ideal cascade that all external flows (with their corresponding isotopic concentrations) may be expressed in terms of the value function and the separative work for an ideal cascade. The generalizations of equations (10), (11), and (12) are

$$U_{\text{Total}} - \sum_{i=1}^n S_i V(X_i) = 0, \quad (13)$$

$$\sum_{i=1}^n S_i X_i = 0, \quad (14)$$

$$\sum_{i=1}^n S_i = 0. \quad (15)$$

where S_i = mass flow of stream i , and

$i = 1, 2, 3, \dots, n \equiv$ number of streams entering and leaving cascade.

If the operating costs are taken to be proportional to the separative work in the gaseous diffusion process, this allows us to write an expression to determine the unit costs (C) associated with a stated

production rate. For the case of one product, rearrangement of (10) yields (assigning a zero unit cost to the separative work content of waste)

$$PC_p = FC_f + C_v [PV(X_p) + WV(X_w) - FV(X_f)] \quad (16)$$

For a stated product flow, product and feed concentration, cost of feed, and cost of separative work, the optimum waste concentration can be determined by differentiating equations (11), (12) and (16) with respect to X_w and making the appropriate substitutions:

$$\frac{\partial W}{\partial X_w} = \frac{\partial F}{\partial X_w} \quad (12')$$

$$W = X_f \frac{\partial F}{\partial X_w} - X_w \frac{\partial W}{\partial X_w} \quad (11')$$

$$= (X_f - X_w) \frac{\partial F}{\partial X_w}$$

$$C_f \frac{\partial F}{\partial X_w} + C_v [WV'(X_w) + V(X_w) \frac{\partial W}{\partial X_w} - V(X_f) \frac{\partial F}{\partial X_w}] = 0 \quad (16')$$

$$C_f \frac{\partial F}{\partial X_w} = -C_v [V'(X_w)(X_f - X_w) \frac{\partial F}{\partial X_w} + V(X_w) \frac{\partial F}{\partial X_w} - V(X_f) \frac{\partial F}{\partial X_w}]$$

$$C_f = C_v [V(X_f) - V(X_w) - (X_f - X_w) V'(X_w)] \quad (17)$$

From the given or stated conditions, the only unknown in equation (17) is the waste concentration X_w . Furthermore, when equation (17) is solved for the waste concentration, X_w , it will be optimal for the stated conditions, due to the manner in which equation (17) was derived.

Although equation (17) is not complete, since it does not take into consideration such items as multiple product concentrations, present value, etc., it should lend some insight as to the basis for this algorithm. For example, the stated product, P , and the product concentration, X_p , are supplied as input in the form of a demand schedule. The cost of feed, C_f , and feed concentration, X_f , are also known for a specific case. It should be apparent, then, that the primary function of the dynamic programming section of this algorithm is to select the appropriate costs of separative work, C_v , and the corresponding waste concentration, X_w , which satisfy a more general expression of equation (17) throughout the stated campaign period.

NO ERRORS WERE ENCOUNTERED WHILE READING AND PREPARING THE DATA. EVERYTHING SEEMS TO BE A-OK FOR EXECUTION OF THE PROGRAM.

THIS IS A SAMPLE OF

INFORMATION THAT CAN

BE PRINTED ON

THIS PAGE

----INPUT DATA----

GENERAL INPUT FOR CASE STUDY

NUMBER OF YEARS FOR STUDY	10	BASE YEAR	1812
MAX. FEED FROM TAILS STOCKPILE (MTU)	0.	INTEREST RATE	.
MIN. CONCENTRATION DIFFERENCE	.	INITIAL DC/DP	0.
INITIAL PRODUCT SURPLUS (MTU)	0.	XBAR	.
PRODUCT SURPLUS CONCENTRATION	.	TOLERANCE (MTU)	0.
NATURAL FEED CONCENTRATION	.	DISCOUNT RATE	.

--RULE FOR SALE OF AEC NORMAL SURPLUS--

MIN. ANNUAL SALES BY MINING INDUSTRY FO (MTU)	0.
AEC MINIMUM STOCK-PILE REQUIREMENT (MTU)	0.
FRACTION OF DEMAND IN EXCESS OF FO ALLOTTED TO AEC SALES	.
1ST. YEAR IN WHICH SALES ARE PERMITTED	0

--FEED CONVERSION COSTS--

CONVERSION COST U308 TO UF6 (\$/KGU)	0.
CONVERSION COST U03 TO UF6 (\$/KGU)	0.

---DEPRECIATION AND BURDEN INPUT---

MAXIMUM DEPRECIATION	0.
MINIMUM DEPRECIATION	0.
BURDEN FLOOR	0.
MAXIMUM BURDEN ABOVE FLOOR	0.
MINIMUM BURDEN ABOVE FLOOR	0.
ESTIMATED SATURATION	0.

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ANNUAL INPUT FOR CASE STUDY

YEAR	FEED PRIORITY	WT. FRACTION FOR XW	FEED COSTS \$/KGU AS UF6 FOR DC/DPF	MISC. COSTS (\$MM)	COST TO BE DEPRECIATED (\$MM)	FRACTION DEPRECIATED	FEED COSTS (\$/KGU) AS UF6 IF FEED PURCHASE OR SALE BY AEC IS REQUIRED	NEW PLANT CONSTRUCTION
1812	00000	.	0.	0.	0.	.	0.	0.
1813	00000	.	0.	0.	0.	.	0.	0.
1814	00000	.	0.	0.	0.	.	0.	0.
1815	00000	.	0.	0.	0.	.	0.	0.
1816	00000	.	0.	0.	0.	.	0.	0.
1817	00000	.	0.	0.	0.	.	0.	0.
1818	00000	.	0.	0.	0.	.	0.	0.
1819	00000	.	0.	0.	0.	.	0.	0.
1820	00000	.	0.	0.	0.	.	0.	0.
1821	00000	.	0.	0.	0.	.	0.	0.

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PRODUCT REQUIREMENTS (MTU)

YEAR	TYPE 1			TYPE 2			TYPE 3			TYPE 4		
	S	SX	SVX	S	SX	SVX	S	SX	SVX	S	SX	SVX
1812	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1813	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1814	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1815	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1816	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1817	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1818	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1819	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1820	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1821	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

SS

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MISCELLANEOUS DATA FOR PRODUCT TYPES

YEAR	TYPE 1				TYPE 2				TYPE 3				TYPE 4			
	OPTION NOT 0	OPTION FRACTION	FEED COST \$/KGU	OPTION XW	OPTION NOT 0	OPTION FRACTION	FEED COST \$/KGU	OPTION XW	OPTION NOT 0	OPTION FRACTION	FEED COST \$/KGU	OPTION XW	OPTION NOT 0	OPTION FRACTION	FEED COST \$/KGU	OPTION XW
1812	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.
1813	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.
1814	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.
1815	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.
1816	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.
1817	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.
1818	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.
1819	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.
1820	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.
1821	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.	0	0.	0.	.

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FEED STOCKPILES

STOCKPILE 1 (ENRICHED UO3)

YEAR	CONC	MTU	CONC	MTU	CONC	MTU	CONC	MTU	CONC	MTU
INITIAL	.	0.	.	0.	.	0.	.	0.	.	0.
1812	.	0.	.	0.	.	0.	.	0.	.	0.
1813	.	0.	.	0.	.	0.	.	0.	.	0.
1814	.	0.	.	0.	.	0.	.	0.	.	0.
1815	.	0.	.	0.	.	0.	.	0.	.	0.
1816	.	0.	.	0.	.	0.	.	0.	.	0.
1817	.	0.	.	0.	.	0.	.	0.	.	0.
1818	.	0.	.	0.	.	0.	.	0.	.	0.
1819	.	0.	.	0.	.	0.	.	0.	.	0.
1820	.	0.	.	0.	.	0.	.	0.	.	0.
1821	.	0.	.	0.	.	0.	.	0.	.	0.

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FEED STOCKPILES

STOCKPILE 2 (DEPLETED U03)

YEAR	CONC	MTU	CONC	MTU	CONC	MTU	CONC	MTU	CONC	MTU
INITIAL	.	0.	.	0.	.	0.	.	0.	.	0.
1812	.	0.	.	0.	.	0.	.	0.	.	0.
1813	.	0.	.	0.	.	0.	.	0.	.	0.
1814	.	0.	.	0.	.	0.	.	0.	.	0.
1815	.	0.	.	0.	.	0.	.	0.	.	0.
1816	.	0.	.	0.	.	0.	.	0.	.	0.
1817	.	0.	.	0.	.	0.	.	0.	.	0.
1818	.	0.	.	0.	.	0.	.	0.	.	0.
1819	.	0.	.	0.	.	0.	.	0.	.	0.
1820	.	0.	.	0.	.	0.	.	0.	.	0.
1821	.	0.	.	0.	.	0.	.	0.	.	0.

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FEED STOCKPILES

STOCKPILE 3' (INITIAL TAILS)

CONC	MTU	CONC	MTU	CONC	MTU	CONC	MTU	CONC	MTU
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

STOCKPILE 4 (NORMAL U308)

YEAR	MTU
INITIAL	0.
1812	0.
1813	0.
1814	0.
1815	0.
1816	0.
1817	0.
1818	0.
1819	0.
1820	0.
1821	0.

STOCKPILE 5 (NORMAL UF6)

YEAR	MTU
INITIAL	0.
1812	0.
1813	0.
1814	0.
1815	0.
1816	0.
1817	0.
1818	0.
1819	0.
1820	0.
1821	0.

PLANT DATA

YEAR	PLANT 1					PLANT 2					PLANT 3					PLANT 4				
	PL. DES	MAX. POWER LEVEL	MIN. POWER LEVEL	IMPROV FACTOR	UNIT POWER COST MI/KWH	PL. DES	MAX. POWER LEVEL	MIN. POWER LEVEL	IMPROV FACTOR	UNIT POWER COST MI/KWH	PL. DES	MAX. POWER LEVEL	MIN. POWER LEVEL	IMPROV FACTOR	UNIT POWER COST MI/KWH	PL. DES	MAX. POWER LEVEL	MIN. POWER LEVEL	IMPROV FACTOR	UNIT POWER COST MI/KWH
1812	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.
1813	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.
1814	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.
1815	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.
1816	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.
1817	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.
1818	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.
1819	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.
1820	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.
1821	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.	0	0.	0. 0.	0.	0.

POWER COST DATA

SURCHARGE MI/KWH	ESC. RATE	INITIAL POWER	SURCHARGE MI/KWH	ESC. RATE	INITIAL POWER	SURCHARGE MI/KWH	ESC. RATE	INITIAL POWER	SURCHARGE MI/KWH	ESC. RATE	INITIAL POWER
0.	.	0.	0.	.	0.	0.	.	0.	0.	.	0.

PLANT DATA-- PLANT DESCRIPTION NUMBER 1

PLANT 1

PLANT 2

PLANT 3

PLANT 4

POWER CURVE DATA

POWER LEVEL MW	SEPARATIVE CAPACITY KG/D	INC. SEP CAPACITY KG/MWD
----------------------	--------------------------------	--------------------------------

POWER LEVEL MW	SEPARATIVE CAPACITY KG/D	INC. SEP CAPACITY KG/MWD
----------------------	--------------------------------	--------------------------------

POWER LEVEL MW	SEPARATIVE CAPACITY KG/D	INC. SEP CAPACITY KG/MWD
----------------------	--------------------------------	--------------------------------

POWER LEVEL MW	SEPARATIVE CAPACITY KG/D	INC. SEP CAPACITY KG/MWD
----------------------	--------------------------------	--------------------------------

CASCADE COST DATA (\$/MM)

	A	B	C	A	B	C	A	B	C	A	B	C
SHUTDOWN	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
START-UP	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
OPERATION	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
DIST. POWER	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
STANDBY	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
STANDBY (D)		0.			0.			0.			0.	

----COMPUTED RESULTS----

A. CASE SUMMARY

ANNUAL DATA- YEAR	1812	1813	1814	1815	1816	1817	1818	1819	1820	1821
1. OPERATING SCHEDULE										
POWER LEVEL (MW)										
PLANT 1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
PLANT 2	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
PLANT 3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
PLANT 4	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
SEP WORK SOLD (MTU)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
SURPLUS SEP WORK (MTU)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL SEP WORK (MTU)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM SEP WORK SLD (MTU)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM SUR SEP WORK (MTU)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM. SEP. WORK (MTU)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM. NP SEP. WORK	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CASCADE XW	.	.	.	.	.	.	.	.	.	.
DCDP	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM. PROD. SRPLUS(MTU)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
DDP COST SEP WORK(\$/KGU)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOT COST SEP WORK(\$/KGU)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

FINAL STOCKPILES (END OF PERIOD UNDER STUDY)

NORMAL U308		NORMAL UF6		UO3		VAL
MTU	VAL	MTU	VAL	MTU	MTX	
0.	0.	0.	0.	0.	0.	0.

ANNUAL DATA- YEAR	1812	1813	1814	1815	1816	1817	1818	1819	1820	1821
2. COSTS (\$MM/YR.)										
RAW POWER	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
DISTRIBUTION POWER	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL POWER COST	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
OPERATION	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
SHTDOWN,STNOBY,STRUP	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOT. CASC. VAR. COST	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
DEPRECIATION	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ADDED FACTOR	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NEW CAP. DEPRECIATION	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOT. CASC. FIX. COST	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOT COST WO/INT	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM RAW POWER COST	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM DISTRIBUTION POWER	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM TOTAL POWER COST	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM OPERATION	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM SHTDN,STNOBY,STRUP	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM OTHER	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM CAS VAR COST	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM CAS VAR COST W/I	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM DEPRECIATION WO/I	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM DEPRECIATION W/INT	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM ADDED FACTOR WO/I	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM ADDED FACTOR W/INT	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM NEW CAP DEP WO/I	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM TOT CAS F C WO/I	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM TOT CAS F C W/I	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM. NP SEP. WORK CST.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM. AEC VAR. FEED CST	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM AEC VAR FD CST W/I	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM AEC VAR CST WO/I	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM. AEC VAR. CST W/IN	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM. TE FEED COST	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM. TE FEED CST W/INT	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM. TE FEED AND AEC VAR. COST WO/INT	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM. TE FEED AND AEC VAR. COST W/INT	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM TOT COST WO/I	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM TOT COST W/I	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

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B. AEC FEED DETAIL

ANNUAL DATA- YEAR	1812	1813	1814	1815	1816	1817	1818	1819	1820	1821
1. FEEDS RECEIVED										
NORMAL U308 (MTU)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NORMAL UF6 FROM TE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NORMAL UF6 PURCHASED	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
U03- MTU	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
MTX	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
MTV	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
2. CASCADE FEEDS										
DEPL UF6- MTU	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
MTX	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
MTV	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NORMAL U308 (MTU)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NORMAL UF6 (MTU)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
U03- MTU	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
MTX	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
MTV	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
3. FEED SALES										
NORMAL U308	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NORMAL UF6	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
U03 (EQUIVALENT UF6)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
4. FEED STCKPL INITIAL										
DEPL UF6-MTU	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
MTX	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
MTV	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NORM U308 (MTU)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NORM UF6 (MTU)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
U03- MTU	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
MTX	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
MTV	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
5. VAR. FEED CST (\$MM/YR.)										
UF6 PURCHASED	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
U308 CONVERSION	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
U03 CONVERSION	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
REC. FROM NORMAL SALES	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NET COSTS	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM CONV COST W/INT	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM CONV COST W/INT	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM SALES W/INT	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CUM SALES W/INT	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

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C. TOLL ENRICHER FEED DETAIL

YEAR	UF6 PURCHASED (MTU/YR)					UF6 COSTS (\$MM/YR)				
	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TOTAL	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TOTAL
1812	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1813	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1814	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1815	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1816	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1817	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1818	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1819	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1820	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
1821	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

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D. CASH INFLOW \$MM

YEAR	TYPE 1		TYPE 2		TYPE 3		TYPE 4	
	FEED SUPPLIED	FEED NOT SUPPLIED	FEED SUPPLIED	FEED NOT SUPPLIED	FEED SUPPLIED	FEED NOT SUPPLIED	FEED SUPPLIED	FEED NOT SUPPLIED
1812	0.	0.	0.	0.	0.	0.	0.	0.
1813	0.	0.	0.	0.	0.	0.	0.	0.
1814	0.	0.	0.	0.	0.	0.	0.	0.
1815	0.	0.	0.	0.	0.	0.	0.	0.
1816	0.	0.	0.	0.	0.	0.	0.	0.
1817	0.	0.	0.	0.	0.	0.	0.	0.
1818	0.	0.	0.	0.	0.	0.	0.	0.
1819	0.	0.	0.	0.	0.	0.	0.	0.
1820	0.	0.	0.	0.	0.	0.	0.	0.
1821	0.	0.	0.	0.	0.	0.	0.	0.

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YEAR	SURPLUS CASH INFLOW \$MM	TOTAL CASH INFLOW \$MM	NET CASH FLOW \$MM	DISCOUNTED CASH FLOW \$MM	CUMULATED DISCOUNTED CASH FLOW \$MM	POWER COST/SEP WORK \$1KGU
1812	0.	0.	0.	0.	0.	0.
1813	0.	0.	0.	0.	0.	0.
1814	0.	0.	0.	0.	0.	0.
1815	0.	0.	0.	0.	0.	0.
1816	0.	0.	0.	0.	0.	0.
1817	0.	0.	0.	0.	0.	0.
1818	0.	0.	0.	0.	0.	0.
1819	0.	0.	0.	0.	0.	0.
1820	0.	0.	0.	0.	0.	0.
1821	0.	0.	0.	0.	0.	0.

E. DISCOUNTED COST SUMMARY

ANNUAL DATA- YEAR	1812	1813	1814	1815	1816	1817	1818	1819	1820	1821
1. GOVERNMENT										
TOT. SEP. WK. VAR. COST	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
SALE OF SEP. WORK	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
FEED COMPONENT	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ENRICHED U235 REVENUE	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
SALE OF SEP WORK	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ENR U235 REVENUE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
SALE OF SEP WK	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
ENR U235 REV	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
FEED TO MKT REVENUE	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
NET CASH FLOW	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
NET CASH FLOW	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NET CASH FLOW	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
DEPREC. AND BURDEN	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NET RETURN	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
NET RETURN	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NET RETURN	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
2. CUSTOMER										
COST OF SEP. WORK	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
COST OF SEP. WORK	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
COST OF MKT. FEED	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
COST OF GOVT. FEED	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL CASH OUTFLOW	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
TOTAL CASH OUTFLOW	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL CSH OUTFL	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
3. MINING INDUSTRY										
REVENUE FROM FEED SOLD	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
4. TOTAL ENTERPRISE COST										
AEC CONTROLLABLE COST										
LESS FEED SOLD PLUS										
T.E. FEED COSTS	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
UNIT COST OF SEPARATIVE WORK WITH CHARGE(\$/KGU)				0.						
UNIT COST OF SEPARATIVE WORK W/O CHARGE(\$/KGU)				0.						
CHARGE(\$/KGU)				0.						
OUT-OF-POCKET UNIT COST OF SEPARATIVE WORK(\$/KGU)				-0.						

CUMULATIVE DATA-
YEAR

1. GOVERNMENT

	1812	1813	1814	1815	1816	1817	1818	1819	1820	1821
TOT. SEP. WK. VAR. COST	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
SALE OF SEP. WORK	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
FEED COMPONENT	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ENRICHED U235 REVENUE	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
SALE OF SEP. WORK	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ENR U235 REVENUE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
SALE OF SEP. WK	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
ENR U235 REV	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
FEED TO MKT REVENUE	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
NET CASH FLOW	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
NET CASH FLOW	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NET CASH FLOW	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
DEPREC. AND BURDEN	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NET RETURN	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
NET RETURN	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NET RETURN	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

2. CUSTOMER

COST OF SEP. WORK	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
COST OF SEP. WORK	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
COST OF MKT. FEED	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
COST OF GOVT. FEED	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL CASH OUTFLOW	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
TOTAL CASH OUTFLOW	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL CSH OUTFL	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

3. MINING INDUSTRY

REVENUE FROM FEED SOLD	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
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4. TOTAL ENTERPRISE COST

AEC CONTROLLABLE COST										
LESS FEED SOLD PLUS										
T.E. FEED COSTS	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

UNIT COST OF SEPARATIVE WORK WITH CHARGE(\$/KGU)	0.
UNIT COST OF SEPARATIVE WORK W/O CHARGE(\$/KGU)	0.
CHARGE(\$/KGU)	0.
OUT-OF-POCKET UNIT COST OF SEPARATIVE WORK(\$/KGU)	-0.

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ANNUAL DATA- YEAR	1812	1813	1814	1815	1816	1817	1818	1819	1820	1821
1. GOVERNMENT-DETAIL										
SALE OF SEP. WORK										
TYPE 1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TYPE 2	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TYPE 3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
FEED COMPONENT										
TYPE 1	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
TYPE 2	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
TYPE 3	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
ENRICHED U235 REVENUE										
TYPE 1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TYPE 2	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TYPE 3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
SALE OF SEP WORK										
TYPE 1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TYPE 2	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TYPE 3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ENR U235 REVENUE										
TYPE 1	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
TYPE 2	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
TYPE 3	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
2. CUSTOMER-DETAIL										
COST OF MKT. FEED										
TYPE 1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TYPE 2	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TYPE 3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
3. TYPE 4										
SALE OF SEP. WORK	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
FEED COMPONENT	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
ENRICHED U235 REVENUE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
SALE OF SEP WK	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ENR U235 REVENUE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
4. AEC SUMMARY										
NET CASH FLOW	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
NET CASH FLOW	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NET CASH FLOW	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NET RETURN	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
NET RETURN	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NET RETURN	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

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CUMULATIVE DATA-
YEAR

	1812	1813	1814	1815	1816	1817	1818	1819	1820	1821
1. GOVERNMENT-DETAIL										
SALE OF SEP. WORK										
TYPE 1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TYPE 2	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TYPE 3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
FEED COMPONENT										
TYPE 1	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
TYPE 2	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
TYPE 3	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
ENRICHED U235 REVENUE										
TYPE 1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TYPE 2	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TYPE 3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
SALE OF SEP WORK										
TYPE 1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TYPE 2	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TYPE 3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ENR U235 REVENUE										
TYPE 1	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
TYPE 2	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
TYPE 3	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
2. CUSTOMER-DETAIL										
COST OF MKT. FEED										
TYPE 1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TYPE 2	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TYPE 3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
3. TYPE 4										
SALE OF SEP. WORK	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
FEED COMPONENT	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
ENRICHED U235 REVENUE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
SALE OF SEP WK	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ENR U235 REVENUE	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
4. AEC SUMMARY										
NET CASH FLOW	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
NET CASH FLOW	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NET CASH FLOW	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NET RETURN	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.	-0.
NET RETURN	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
NET RETURN	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

DISTRIBUTION

INTERNAL

Standard ORGDP Distribution

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L. L. Anthony, Jr.
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