A COMBINED SIMULATION MODEL OF THE NUCLEAR FUEL CYCLE

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ABSTRACT

Strategies for dealing effectively with the complex nuclear fuel cycle are needed to assure the availability of the required nuclear energy portion of U.S. energy supplies. The vertical integration approach to assuring uranium fuel supplies is achieved through control or ownership of fuel cycle stages. Global system analysis is facilitated by identifying crucial control points in the fuel cycle.

A GASP IV simulation model of the production and inventories of the sequentially produced nuclear fuel is developed and includes the optional feedback loop associated with the recycle of uranium from spent fuel. The model is verified to assure accurate fuel cycle representation by comparing derived material flows to 1970-75 historical data. The model is then applied to the 1977-1994 horizon to verify the practicality of vertical integration within the fuel cycle and to determine stages in which altered production capacity is appropriate. Results of the simulation analysis using a one-at-a-time search technique using four replications indicate that production capacities throughout the fuel cycle should be increased, in some cases significantly. Additional milling capacity should be added every year and several new refining plants and reprocessing facilities will be needed to assure provision of planned nuclear generated electricity supplies.

INTRODUCTION

Within the nuclear power industry, increasing interest is being focused upon strategies for dealing with the nuclear fuel cycle. The primary reasons for this growing interest lie in the complex cost structure of the fuel cycle, the extensive lead times involved in obtaining the fabricated fuel assemblies used in a reactor, and the uncertainties associated with the management of the discharged spent fuel. Given the apparent importance of nuclear power generation to national energy goals, methodologies that lead to efficient interaction with the nuclear fuel cycle are quite timely.

The nuclear fuel cycle which is shown below in Figure 1 (2), is the sequence of production stages that transform uranium bearing ore into

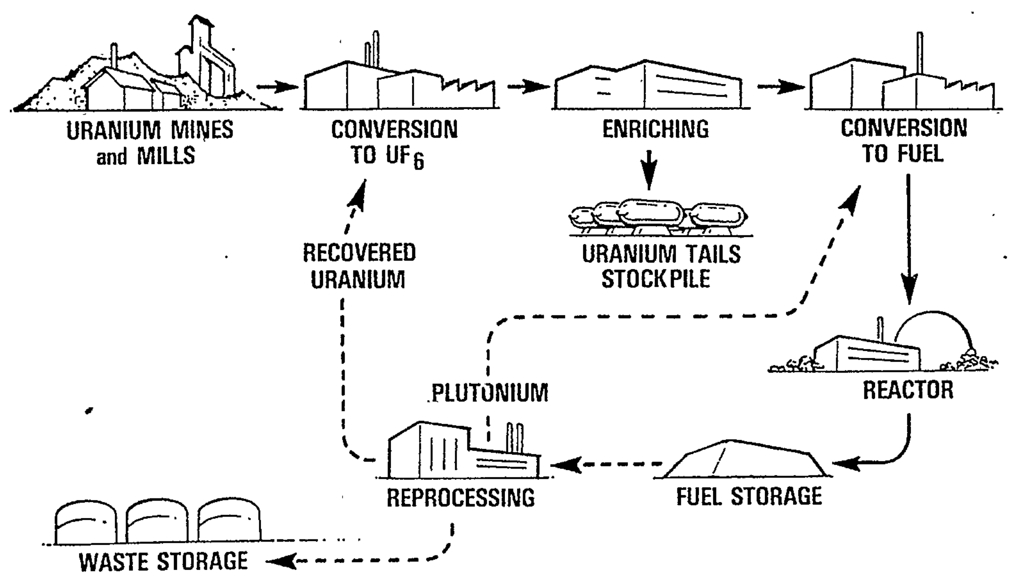

Figure 1. Nuclear Fuel Cycle

reactor fuel and back into the ground in the form of solid waste. As indicated in the figure, uranium ore is mined and milled to produce a raw material called "yellow cake". This yellow cake is processed in a refinery which chemically converts it to UF_6 gas that goes to the enrichment plant where it is mechanically enriched in the radioactive U-235 isotope. The enriched UF_6 gas is converted to UO_2 powder that is pressed into pellets which are sintered and loaded into fuel rods. These operations and the aggregation of the fuel rods into matrices known as fabricated fuel assemblies occur at the fabrication plant. The fuel assemblies are used in a reactor core to generate electricity for approximately three years after which time the fuel is discharged, stored to cool, and then reprocessed. The reprocessing plant separates the spent fuel into plutonium and uranium for recycle into the reactor and solid wastes that are discarded. It should be noted that present federal regulations prohibit reprocessing of spent fuel. Much of the controversy over the advisability of using nuclear power revolves around the question of how spent fuel should be managed. Nevertheless, reprocessing or some other end disposition of spent fuel will soon be permitted to provide at least partial closure of the nuclear fuel cycle.

As was indicated in the above description, the nuclear fuel cycle consists of a series of production stages. Recently, reactor operating utility companies have indicated interest in controlling or owning various stages in the fuel cycle. Ownership can be defined either in the usual sense or as contractual control of production capacity. In either case, the question of which approaches to this vertical integration within the nuclear fuel cycle are best is important to utilities concerned about assuring the availability of reactor fuel. In view of the projected growth of the nuclear power industry and estimates of available uranium supplies, cost effective strategies for interacting with the nuclear fuel cycle to permit utilities to assure the supply of reactor fuel will be necessary.

From a similar perspective the formulation of national energy policies should reflect nuclear fuel availability. The commercial nuclear energy industry including fuel cycle participants is heavily regulated. Government policies and regulations should promote the expansion of those fuel cycle stages that may constrain the attainment of planned levels of nuclear reactor based energy generation. In this paper, approaches to addressing the question of how best to control fuel supply are examined from a production scheduling and inventory management perspective.

CONCEPTUALIZATION

The basis of the model formulation is a conceptualization of the nuclear fuel cycle that is consistent with a production and inventory perspective. This view of the nuclear fuel cycle is constructed by treating each of the stages of the cycle shown in Figure 1 as a production facility and by associating with each such facility an inventory of output. In addition, exploration for uranium ore reserves is treated as a production stage with an associated inventory corresponding to the reserves located. Thus, each stage of the fuel cycle is represented as a basic building block of the type shown in Figure 2 below and first used by Zangwill (7).

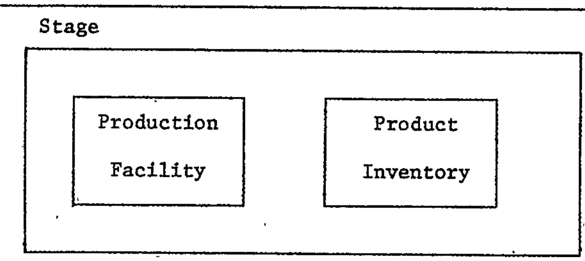

Figure 2. Basic Stage Composition

Under this concept of the stages, the nuclear fuel cycle and its material flows can be represented in the form illustrated in Figure 3. It should be noted that each stage can be expanded into several parallel plants and that the stages of enrichment and irradiation in the reactor can be represented as several stages each of which corresponds to a separate product enrichment.

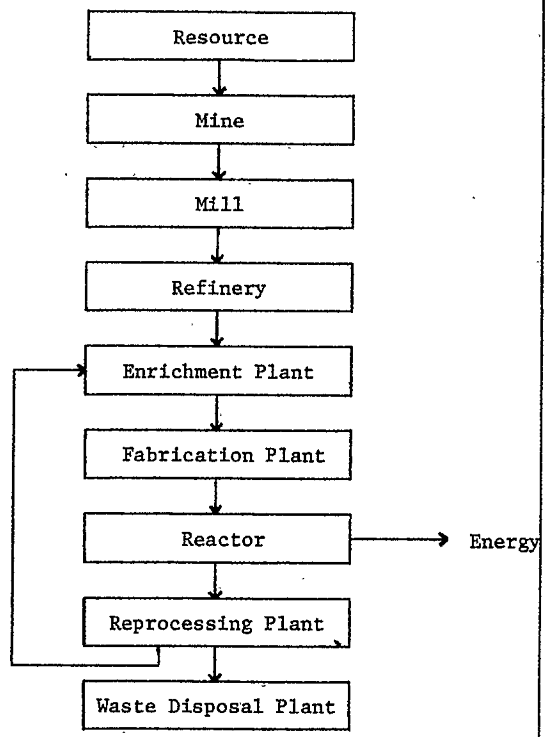

Figure 3. Nuclear Fuel Cycle as Set of Production Stages

In addition, aggregation of several parallel facilities or several enrichments into a single representative stage is also reasonable and this approach is used here.

As is indicated in Figure 3, the output materials from a given stage become the input materials for another stage. However, a model using this representation of the cycle will be "driven" by the demand for energy from the reactor. Thus, conceptually, the nuclear fuel cycle is represented as a cyclic multi-stage production-to-inventory system.

THE SIMULATION MODEL

A GASP IV simulation model is constructed using the system conceptualization described. Although spent nuclear fuel is not presently being reprocessed, it is assumed that reprocessing will be reinitiated. This is reflected in the model by operating the reprocessing plants in the future beginning on an input start-up date. BROWN's (1) polynomial forecasting technique is applied to projections (6) of U.S. nuclear power plant growth to estimate a continuous demand function for fabricated uranium fuel. Present production capacities of the various nuclear fuel cycle stages are obtained from published government documents.(5) Model plant sizes and capacities are developed using the "Environmental Survey of the Uranium Fuel Cycle".(3) The model is driven externally by demand for reactor fuel. Internally, each stage is driven by the production rate of the succeeding stage. Published government cost estimates (4) are used for the unit production costs at each stage. Inventory holding costs are assumed linear while production costs are quadratic functions of production rate.

The simulation model is validated by comparison of predicted fuel material flows to those experienced in the interval 1970-1975. Validation is considered successful because model predictions of uranium utilization and spent-fuel generation both fall within 3% of actual experience.

Once validated, the model is applied to nuclear fuel requirements projections for the interval 1977-1994. The objective of the experiment is to determine the times at which additional plants of the model size should begin operation in order to minimize overall production and inventory costs. In addition, an indication of the most effective intervention points in the fuel cycle for a utility attempting to assure fuel supply are sought.

ANALYSIS

The solution is approximated by applying the one-at-a-time search technique using four replications. The search begins by using government plant capacity projections (5) as starting points. Using model plant sizes, production at any stage at a given point in time fixes the demand upon the preceeding stage at a defined earlier point in time. The search proceeds by varying the start-up dates of each new plant relative to those of other new plants until a minimum cost is found. The resulting capacity expansion scenario is then shifted in time until a minimum system cost is determined. The process is then repeated. Repetition of the experiment is continued until a new iteration yields a cost reduction that is less than 1% of the total minimum fuel cycle cost. Subsequently, revised scenarios are assumed but over the various trials, no case led to a cost that was less than 118% of the minimum cost found using the original scenario. While the minimum cost determined may not be a global minimum, no better solution was found and continued application of the model may improve the confidence interval on the minimum cost.

Specific results of the simulation experiment are:

1. Additional uranium mill capacity equivalent to 1600 tonnes of ore per day should be created every year for the next 17 years except for 1983 in which two such mills should be added.

2. Refinery capacity of 5000 tonnes of uranium per day should start operation in 1979, 1981, 1983, 1988, 1991, and 1994.

3. Uranium enrichment capacity should be increased in 1987 by 10,500 tonnes of separative work units.

4. Fuel fabrication plants with capacity of 3 tonnes of uranium oxide per day should begin operation in 1981 and 1987.

5. Nuclear fuel reprocessing capacity should be increased in each of 1977, 1981, and 1988 by 900 tonnes per year.

6. Uranium fuel should be stockpiled as a basic resource and as enriched uranium hexafluoride gas.

Thus, the simulation results indicate that significant expansion of fuel cycle production capacities is required to provide adequate supplies of uranium fuel. In addition, the appropriate stockpile points in the fuel cycle are those that are either least expensive or are close enough to the reactor to be accessed and utilized rapidly.

SUMMARY

A GASP IV simulation model of the nuclear fuel cycle is constructed. Analysis of the model using a one-at-a-time search technique shows that the costs associated with the interactions of the production stages can be significantly reduced and possibly minimized by adding stage wise additional plant capacities in a coordinated complete cycle scenario. Utility companies can apply this model with company specific data to assess their own strategies for participation in the fuel cycle. Significant expansions of fuel cycle stage capacities appear necessary and stockpiling nuclear fuel can be used to help assure fuel supply.

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