NUFACTS: A TOOL FOR THE ANALYSIS OF NUCLEAR DEVELOPMENT POLICIES

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ABSTRACT

NUFACTS, the Nuclear Fuel Cycle Activity Simulator, is a combined continuous/discrete simulation of the nuclear power economy. This model has been useful in the evaluation of nuclear development policies as it projects the economic and resource impacts attributable to a given policy. A recent application of NUFACTS has involved the economic evaluation of plutonium recycle options in light-water reactors.

Based upon the GASP IV simulation language, NUFACTS provides a highly flexible means of simulating a wide variety of nuclear growth scenarios. In its present form most planned reactor concepts can be studied. To achieve this capability a model of the nuclear fuel cycle has been developed that incorporates functions related to the control over the pattern of development of nuclear power as well as to the detailed operation of individual reactors.

INTRODUCTION

The future contribution of nuclear power to this country's supply of electricity faces many uncertainties. Among these are questions concerning the development of alternate reactor systems, the growth and commercialization of fuel cycle industries, and the desirability of plutonium recycle in light-water reactors. Resolution of many issues facing the growth of nuclear power depends upon the ability to forecast the impacts which alternate growth scenarios are likely to have in terms of economic expenditures, resource consumption, and required growth of supporting industries. A computer code known as NUFACTS (Nuclear Fuel Cycle Activity Simulator) has been developed by Battelle's Columbus Laboratories for application to the analysis of nuclear policy issues. NUFACTS uses the GASP IV simulation language (1) and is a combined discrete event/continuous state simulation. The program can monitor reactor operations by displaying the costs of producing electricity, the consumption of resources, and the installed generating capacity along with many additional variables.

The development of NUFACTS has relied heavily upon the experience with the Nuclear Energy Electrical Demand Simulation (NEEDS) (2). Although the codes are similar in function, substantial differences exist in the modeling approach which has resulted in an enhanced role for NUFACTS in the analysis of nuclear energy issues. NUFACTS provides a flexible means for defining alternate scenarios and for obtaining the desired output related to both system economics, utilization of resources, and demand for fuel cycle services.

This paper describes both the structure of the model and the application of the model to the evaluation of plutonium recycle in light-water reactors. Before presenting the structure of the model, the nature of the system being modeled is discussed as are some of the important issues in the development of nuclear power.

The basic elements of the system modeled by NUFACTS are displayed in Figure 1. The processes or industries in this diagram represent the flow of fuel to and from a reactor, i.e., the nuclear fuel cycle. In this system for light-water reactors (LWRs) uranium ore is mined, converted to U_3O_8 or "yellowcake," and then converted to gaseous UF_6. This material is then enriched to increase the concentration of the uranium isotope U-235 from its natural concentration of .711% to approximately 3%. After enrichment the uranium is fabricated into fuel assemblies which are then shipped to the reactor. LWRs refuel approximately once a year and replace 1/4 to 1/3 of their fuel assemblies at each reloading. The spent fuel then enters the "back-end" of the fuel cycle after cooling at the reactor site. Currently, however, the back-end of the fuel cycle has not been closed (i.e., there are no commercial reprocessing facilities operating). Therefore, spent fuel assemblies are accumulating in reactor storage pools and the available space is rapidly being used up. If allowed, reprocessing would separate various waste products from the spent fuel and recover U-235 and plutonium isotopes. These materials can be fabricated into fuel assemblies once again and be reinserted into reactors, thus reducing the amount of fresh uranium required for each loading.

Investigation of nuclear power growth alternatives must consider not only the reactor systems to be used, but also the timing of changes in the operating modes of LWR's, the rate at which reprocessing capacity comes on line, and rate of introduction of new reactor systems. To create a tool which could provide significant inputs to nuclear power analyses, a computer simulation with the following functions was desired:

1. (1) Simulation of both uranium and thorium fuel cycles
2. (2) Addition of discrete reprocessing units
3. (3) Simulation of LWR operating mode switches
4. (4) Maintenance of material inventories in the fuel cycle
5. (5) Calculation of the cost of producing electricity
6. (6) Control of the mix of reactors annually introduced
7. (7) Generation of fuel cycle industry requirements as a function of time.

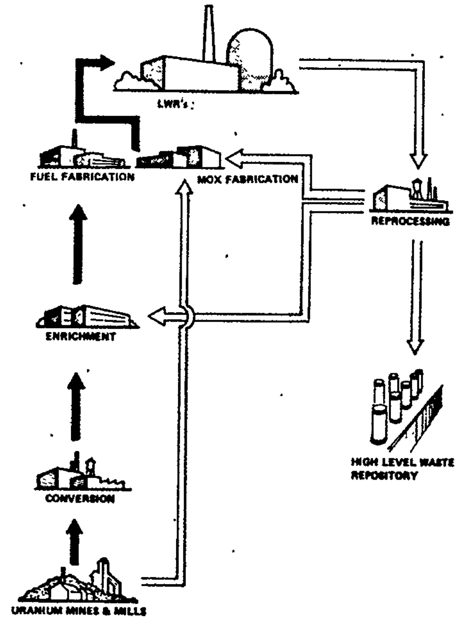

FIGURE 1. NUCLEAR FUEL CYCLE FOR THE LIGHT-WATER REACTOR (LWR)

MODEL STRUCTURE

Of primary importance in the model development, is the need to maintain control over the mix of reactors, i.e., the expansion of the nuclear economy. Thus, the basic problem in modeling the operation of the nuclear fuel cycle is one of determining how to incorporate both the macro and micro aspects of the fuel cycle. Macro aspects pertain to the control over the mix of reactors that are operating at any one time. Micro elements of the model relate to the operation of individual reactors. Achieving an appropriate balance between these factors and still maintain an efficient model are the challenges to this effort.

The microscopic view of the nuclear economy relates to the operation of individual reactors especially as they interact with fuel cycle industries. Cash flows, material flows, and the operating modes of the reactor (i.e., spent fuel disposition) are components of this perspective. The nuclear fuel cycle depicted in Figure 1 illustrates the flow of materials and the processes surrounding the operation of a single reactor. Associated with each process are some costs or charges for services, a movement of fuel, and a length of time for completion of the service. That is, fuel that is loaded into a reactor today may have been mined two years ago and enriched one year ago.

The GASP IV simulation language was chosen as the basis for this modeling effort as it was desired that the final product be transferable. Also, the operation of the nuclear economy was viewed as primarily a discrete event system with some continuous processes occurring. To model the system, entities and the attributes that describe them must be defined along with events. Within NUFACTS two basic types of entities have been defined. The first relates to the micro model and is a reactor set. Many reactor sets operate at any one time. The next entity is a generic reactor such as an LWR or liquid metal fast breeder reactor, LMFBR. Many attributes are used to describe these broad types of reactors. We also defined nine events and one continuous process. During an event the system status can change by alteration of attribute values, by changes in relationships between entities, and by changes in the number of entities present.

The basic structure of NUFACTS is displayed in Figure 2 and consists of five functional areas. Reactor additions, fuel cycle industry additions, and accumulation of system performance measures relate to the macro-level aspects of the nuclear economy. Reactor operations and fuel cycle operations, however, relate to the micro-level or detail activities of specific reactors or processes. Elements within each functional area refer to discrete events or, in the case of reprocessing of spent fuel, a continuous process. These will be defined in the following sections.

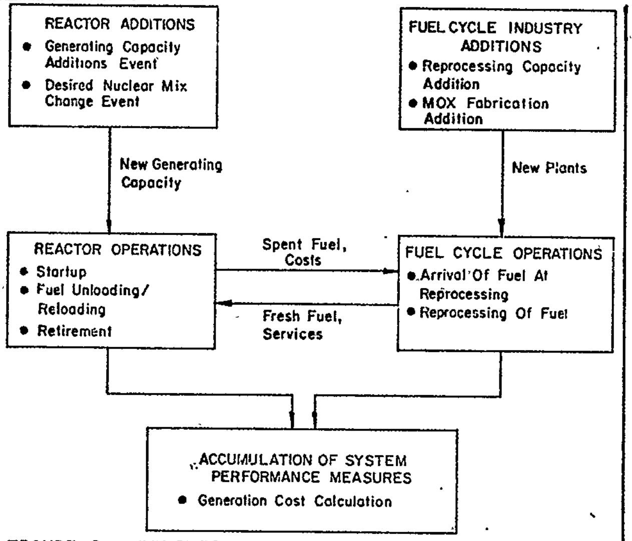

FIGURE 2. RELATION OF NUFACTS FUNCTIONAL COMPONENTS AND DISCRETE EVENTS

Micro Model

The basic unit of analysis within NUFACTS is a reactor set. This may or may not correspond to an actual reactor. For most simulations a reactor set will refer to all reactors of a given type (e.g., LWRs) installed in a one-year period. This implies that they will be treated as one entity and will always operate as a single unit. For example, if five 1000 MWe LWRs are installed in one year, then NUFACTS will maintain one reactor set of size 5000 MWe. By combining reactors in this manner computational efficiency is improved. For short-term simulations, however, specific reactors can be modeled separately. Thus, one type of entity within NUFACTS is the reactor set. As shown in Table 1, each reactor set is described by many attributes.

TABLE 1. ATTRIBUTES USED TO DESCRIBE THE OPERATING REACTOR SET

(1) Date of Introduction
(2) Type of Reactor
(3) Operating Mode
(4) Power in MW electrical
(5) Levelized Fixed Charge
(6) Annual Cumulative Charges
(7) Fuel Quantities in the Reactor
(8) Fuel Quantities in Spent Fuel Storage

Attribute (2), the reactor type, indicates whether the reactor is a PWR, BWR, or LMFBR, for example, while (3), the operating mode, defines how a reactor is operating with respect to the fuel cycle. A PWR could have three modes: throwaway or indefinite storage of its spent fuel; sell its plutonium and recycle its uranium; or recycle both plutonium and uranium in a self-generated recycle mode. The levelized fixed charge (Attribute (5)) is calculated when the reactor comes on line and includes both the fixed charge on the capital and the operating and maintenance costs. This remains constant over the reactor's lifetime while annual charges such as those for fuel and fuel cycle services are accumulated in Attribute (6). Fuel quantities in and outside of the reactor (Attributes (7) and (8)) are broken down by isotope. Discrete events can affect these entities and attributes by adding or removing an operating reactor, assessing charges to the reactor, or moving fuel supplies. These relationships form the basis of the event routines.

To determine the actual quantities of fuel to be loaded into a reactor set, operating characteristics for generic reactor types had to be defined. These are a function of the reactor set's type (e.g., PWR, LMFBR), size in MWe, and operating mode. When these attributes are known, the amount of fuel needed by the reactor can be determined. These characteristics are used by the three events that define reactor operations: start-up, fuel unloading/reloading, and retirement.

The start-up event brings a reactor set or new entity into existence. It obtains fuel for the reactor and defines the appropriate attributes. Times for subsequent unloading/reloading events are set as is a retirement event. Again the time between reloads and the lifetime of the reactor set are functions of the type of reactor.

The central activity of the fuel cycle as modeled by NUFACTS is the unloading of spent fuel from a reactor and associated refueling which is assumed to be a single event. It is from this point in time that demands are made on fabrication, enrichment, conversion, and mining and milling. The back-end of the fuel cycle begins at this point since spent fuel is put into the reactor's storage location until it cools sufficiently for shipping to reprocessing. For reactors which do reprocess fuel, an arrival-at-reprocessing event is scheduled. When the fresh fuel has been obtained and loaded into the reactor, a new unloading event is scheduled for that particular quantity of fuel.

A single reactor is decommissioned by the retirement event which is automatically scheduled by NUFACTS during a start-up event. Final charges are assessed for this reactor and spent fuel is either scheduled to arrive at the reprocessing plant or disposed of in a permanent storage facility. Thus, a reactor set or entity is removed from the system.

Although there is only one event which explicitly deals with the fuel cycle, all front-end industries are modeled implicitly by the collection of fuel during unloading and start-up events. Reprocessing of spent fuel and its subsequent fabrication into a mixed-oxide fuel is modeled as a continuous process. The arrival-at-reprocessing event effectively deposits spent fuel into a queue. This is a discrete event involving individual shipments of spent fuel. Scheduling of this event occurs during the unloading event and takes into account both a "cooling" period for fuel in reactor storage and a transportation time from reactor to reprocessing. The reprocessing facility, however, reduces this backlog at a continuous rate that is a function of its production capacity. In addition to recycled uranium and plutonium, two nuclear waste streams are modeled. The recovered plutonium then moves to mixed-oxide fabrication where it becomes available for use as a fuel in operating reactors. Recovered uranium can also be recycled but must first be re-enriched.

Macro Model

The macro model defines the nature of the growth and development of the nuclear economy. Control is exerted over the growth in both the number of operating reactors and the capacity of fuel cycle industries (i.e., back-end industries). Reactor additions are controlled by manipulation of a second type of entity, generic reactors. The attributes used to describe generic reactors are displayed in Table 2.

These entities and their attributes comprise the Desired Nuclear Mix. This mix defines the priorities and constraints upon reactor introductions and also controls the mode of operation of existing reactors. As an example of the use of these parameters one can consider the LMFBR. For a particular simulation this reactor type may be first introduced in 1995. Therefore, in 1995 a new entity corresponding to the LMFBR will be added to the Desired Nuclear Mix. It may be the highest priority reactor but the number of new operating reactors which are LMFBRs may be constrained by Attributes (5) or (6). The constraints can be revised as the simulation progresses. That is, initially additions of LMFBRs may be limited to 2000 MWe per year but after several years of experience this constraint could be relaxed to 5000 MWe or 10000 MWe. Thus, new technologies such as the breeder reactor may be the preferred reactor for new capacity, but the ability to produce them may not exist.

TABLE 2. ATTRIBUTES USED TO DESCRIBE GENERIC REACTORS (DESIRED NUCLEAR MIX ELEMENTS)

(1) Priority
(2) Reactor Type (e.g., PWR, BWR, HTGR)
(3) Operating Mode (e.g., Throwaway, Self-Generated Recycle)
(4) Maximum fraction of total annual additions composed of this reactor
(5) Maximum annual addition for the reactor
(6) Rate of Introduction
(7) Maximum fraction of total capacity to be composed of this reactor
(8) Maximum fraction of this reactor type operating in this mode
(9) Maximum total capacity of this type

Design of a nuclear power growth scenario can be done in one of three ways through NUFACTS. First, individual reactors or reactor sets can be specified to start at known times. Thus, new capacity additions will occur only at the times specified and the reactors will be only of the type specified by the user. Alternately, an installed capacity scheduled can be specified and new reactors can be started to meet this schedule according to the priorities and constraints of the Desired Nuclear Mix. The installed capacity schedule simply defines the total generating capacity which is required as a function of time and does not specify how or by what reactors this is to be met. The latter is the function of the Desired Nuclear Mix. The third and final approach to adding new capacity is a combination of the two methods. For example, in some scenarios precise startup schedules for reactors in the next ten years may be required, but later in the simulation the Desired Nuclear Mix could be adequate to fill the demand. These operations are depicted in Figure 3.

The events which pertain to this sector of the model are the capacity-additions event, startup event, and desired-nuclear-mix-change event. The capacity-additions event determines the required new capacity and then uses the Desired Nuclear Mix parameters (Table 2) to determine what reactors will actually be started.

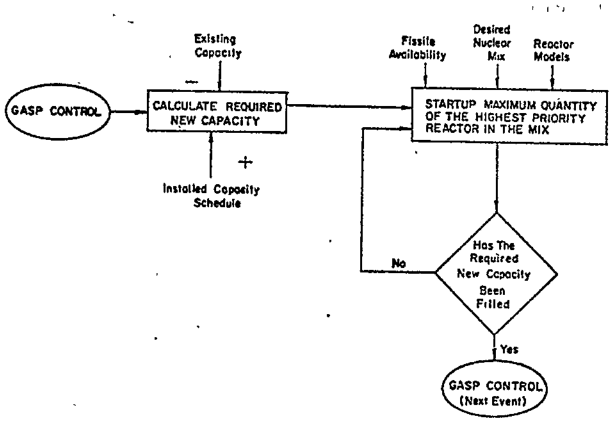

FIGURE 3. GENERATING CAPACITY ADDITIONS ROUTINE

Changes in the priorities and constraints which constitute the Desired Nuclear Mix may be implemented through the desired-nuclear-mix-change event. A reactor may be brought into the mix, taken out of the mix or have its mix parameters changed. These changes must be scheduled by the user with the input data. This event has two main functions in that it can change any attribute of any entity in the Desired Nuclear Mix or it can add/remove an entity (generic reactor concept) to/from the mix.

System performance measures facilitate the monitoring and evaluation of a nuclear growth scenario. Although each event changes one or more of the performance measures, the generation-cost-calculation event accumulates all charges and can be used to generate a periodic report on the system. Charges which have accumulated on operating reactors are summed to determine the total cost of electricity. Fuel cycle performance measures are updated when fuel is obtained for reactors and when reprocessing occurs. Addition or removal of reactors (startup and retirement events) produces changes in aggregate reactor performance measures such as total installed capacity. By identifying the set of performance measures and by making appropriate changes in these measures within event routines, it is possible to monitor many aspects of the nuclear economy.

In the model's present form additions can be scheduled in the capacity of both reprocessing and mixed-oxide fabrication industries. Other fuel cycle industries do not have an installed capacity but rather operate on a demand basis. Thus, for a given installed nuclear generating capacity, there is assumed to be adequate front-end capacity but the availability of recycle fuels such as plutonium depends upon the operating capacity of both reprocessing and mixed-oxide fabrication.

APPLICATIONS

NUFACTS has been used in several recent studies of nuclear power issues. These include:

- An evaluation of fuel cycle options for plutonium utilization for the National Science Foundation, and
- An examination of uranium resource consumption from alternate nuclear power growth scenarios for the National Academy of Sciences.

The application of NUFACTS to the second of these issues, evaluation of plutonium utilization options, is described in detail in the following paragraphs.

One of the most pressing issues related to the development of nuclear power concerns the utilization of plutonium in light-water reactors. The controversy over plutonium recycle results from the small amount of plutonium necessary to make an atomic weapon, the potential environmental impact, and the economics of recycle relative to other options. Various studies have indicated that plutonium recycle is (3,4,5) and is not (6,7) economic. The divergent conclusions result from the differences in the assumed cost for U_3O_8, and the cost of reprocessing. If the Nation is to make a tradeoff between the threat of proliferation of plutonium and the energy that could be generated from plutonium, it is essential to clarify the magnitude of the potential economic benefits of plutonium usage.

It was the intent of this study to re-evaluate the economics of several plutonium utilization options by obtaining the latest data concerning the cost of reprocessing, nuclear growth projections, and the cost of uranium ore as a function of consumption. Following the collection and analysis of the available data, computer runs were made with the NUFACTS code. First, the four basic options to be simulated were defined and formulated. Then, the alternate scenarios were simulated to obtain baseline estimates of the economic impact of each option. Following the analysis of the base cases sensitivity studies were performed to investigate the ranges over which plutonium recycle provided positive benefits to the Nation.

Four distinct options for plutonium utilization were analyzed. They were:

(1) Indefinite storage of spent fuel assemblies from light-water reactors (no plutonium or uranium recycle, no breeders); this option included permanent disposal of spent fuel;
(2) Interim storage and delayed reprocessing of spent fuel, recycling of recovered uranium in light-water reactors, and plutonium utilized in breeder reactors (no plutonium recycle in LWR's);
(3) Delayed reprocessing of spent fuel, uranium and plutonium recycle (no breeder); and
(4) Delayed reprocessing of spent fuel, plutonium recycle, and plutonium utilization in breeders.

Options for plutonium utilization were evaluated from economic and resource consumption perspectives. Health, safety, and environmental aspects of plutonium recycle were not included, although these are essential elements of the decision to recycle plutonium. The economic assessments of plutonium utilization considered both the present value of the total cost of electricity, and the cost of electricity (to consumers) in some future year. Resource consumption was compared to the quantities of ore either known to exist or potentially available.

Simulation Results

The average annual generation cost in mills per kilowatt-hour (for each of the four options) is plotted in Figure 4. By indefinitely storing spent fuel as in Option 1, a rapidly increasing generation cost results by the year 2000. In 2020 the generation cost is 24.23 mills/KWh. With plutonium recycle instituted in 1980 (Option 3), the generation cost is 19.42 mills/KWh in 2000 and 20.86 mills/KWh in 2020. This yields a savings in the cost of electricity of almost 5 percent and 14 percent in the years 2000 and 2020, respectively. In 2000 Option 2 has the highest generation cost, but this is caused by the extensive reprocessing capacity which is required to remove the backlog of spent fuel and provide plutonium for LMFBR startups. This cost later levels off as is evident for Option 4 (plutonium recycle and LMFBR). This result is brought about by the penetration of the LMFBR which, by the end of the simulation period, constitutes almost 35 percent of the total operating capacity.

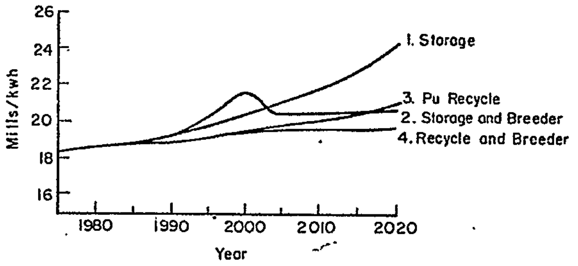

FIGURE 4. AVERAGE GENERATION COSTS FOR U.S. NUCLEAR POWER PLANTS FOR EACH OF THE FOUR OPTIONS

Similar results were obtained for the cumulative discounted cost of electricity. A discount rate of 10 percent is used for these options. Option 4 has the lowest discounted cost, $213.3 billion, Option 3 next with $214.6 billion, then Option 2 with $218.1, and last is Option 1 with $222.3 billion. Since the advantage accrued by the LMFBR is heavily discounted, the percentage of difference between plutonium recycle in LWR's (Option 3) and the breeder options seems to be less than was indicated by the average annual generation cost.

The economic driving factor in all cases is the trend in U_3O_8 price. If, however, the price rises rapidly, due to depletion of higher grade ores as it does in Option 1, significant differences do appear. Thus, when LMFBR penetration drastically reduces U_3O_8 consumption, a tremendous advantage is achieved.

The LMFBR presents a substantial avenue for cost savings in the nuclear economy. This is dependent, however, upon projected LMFBR capital costs and upon adequate supplies of plutonium which, in turn, implies a substantial reprocessing capability.

Plutonium recycle in LWR's without the breeder has a benefit of almost $8 billion in discounted generation costs (about 3.5 percent reduction from the storage option) and reduced U_3O_8 consumption by almost 30 percent through 2020. Although substantially better than the indefinite storage option, the annual generation cost associated with Pu recycle increases with time and thus Pu recycle alone provides only a short-term relief from the fuel constraint.

It can be concluded that on the basis of economics early reprocessing and plutonium recycle along with rapid breeder introduction is the best case while temporary storage of spent fuel and reprocessing in time for breeder introduction is also economically attractive. Plutonium recycle with no LMFBR is much better than no recycle; but without the breeder, uranium consumption becomes critical for all pure LWR options.

SENSITIVITY ANALYSIS

In recent years estimates of the magnitude of several parameters critical to the evaluation of plutonium recycle have changed dramatically. Among these are the projected growth rate for nuclear power, uranium ore availability and price, reprocessing costs, and the timing of reprocessing startup in the U.S. The flexibility of NUFACTS has facilitated sensitivity studies of these and other parameters to be made. As a result of these studies, the benefits of plutonium recycle were shown to be positive for most reasonable parameter variations. Only when combinations of parameters were chosen to be unfavorable to recycle were the benefits negated.

SUMMARY

In its present form NUFACTS can be used to generate fuel cycle industry requirements as a function of time for very complex growth scenarios. This could include spent fuel storage requirements for either aggregate or individual reactors. With respect to reprocessing operations NUFACTS can display the transient behavior which could result during a plant's first years of operation by tracing the buildup and removal of the spent fuel backlog. Similarly, the impact upon the nuclear power economy of a new reactor system can be modeled in great detail. LMFBR or HTGR introductions and their impacts upon fuel cycle requirements, fissile availability, and the operation of existing reactors could be shown.

These are just a few of the potential applications for a simulation of this type. NUFACTS is especially suitable to these analyses because it provides a flexible modeling tool which can simulate most planned reactor systems and can do so at various levels of detail. The modular design and the event structure makes addition, subtraction, or modification of events possible without disrupting the overall logic of the program.

AKNOWLEDGEMENTS

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REFERENCES

(1) Pritsker, A.A.B., The GASP IV Simulation Language, Wiley-Interscience, New York (1974).
(2) Willke, T.L., "NEEDS: Nuclear Energy Electrical Demand Simulation", Simulation, 26 (2), 33-42 (1976).
(3) ERDA, "Generic Environmental Statement and Mixed Oxide Fuel Draft", WASH-1327, August, 1974.
(4) AGNS, "Nuclear Fuel Cycle Closure Alternatives", April, 1976.
(5) ERDA-33, "Nuclear Fuel Cycle", March, 1975.
(6) Rodger, Pickard, Vallance, "The Throwaway Fuel Cycle", Pickard, Lowe, and Associates.
(7) Resinkoff, Marvin, "Is Reprocessing Cost Justified", NRDC.
(8) Pardue, William, et.al., "Evaluation of Fuel Cycle Options for Plutonium Utilization", Report from Battelle's Columbus Laboratories to the National Science Foundation, October 11, 1976.