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**A Survey of Nuclear  
Fuel-Cycle Codes**

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G. de Saussure  
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DEPARTMENT OF ENERGY

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**A SURVEY OF NUCLEAR FUEL-CYCLE CODES**

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Date Published - April 1981

This Work Sponsored by  
Department of Energy  
Office of Energy Information Validation

\*Energy Division  
†Engineering Physics Division

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operated by  
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## ABSTRACT

At the request of the Office of Energy Information Validation (OEIV), a two-month survey of nuclear fuel-cycle models was undertaken by the Model Evaluation Team of the Oak Ridge National Laboratory (ORNL). This report presents the information forthcoming from the survey. Of the nearly thirty codes reviewed in the survey, fifteen of these codes have been identified as potentially useful in fulfilling the tasks of the Nuclear Energy Analysis Division (NEAD) as defined in their FY 1981-1982 Program Plan. Six of the fifteen codes are given individual reviews. The individual reviews address such items as the funding agency, the author and organization, the date of completion of the code, adequacy of documentation, computer requirements, history of use, variables that are input and forecast, type of reactors considered, part of fuel cycle modeled and scope of the code (international or domestic, long-term or short-term, regional or national). The report recommends that the Model Evaluation Team perform an evaluation of the EUREKA uranium mining and milling code.

## SECTION 1: INTRODUCTION AND STATEMENT OF PURPOSE

Nuclear energy forecasts by the Energy Information Administration (EIA) of the Department of Energy (DOE) are utilized for planning by government, industry, and the public. These forecasts are generally recognized as authoritative, accurate, and realistic. The production of these nuclear energy forecasts is a service provided by the Nuclear Energy Analysis Division of the EIA (10).

The widespread use of the EIA nuclear energy forecasts reveals their importance. These forecasts play a crucial role in helping formulate U.S. Government energy policies (1), and are employed not only for program planning in various offices of the DOE (such as the Assistant Secretaries for Nuclear Energy, for Policy and Evaluation, for International Affairs, and for Resource Applications), but also by other government agencies including the State Department where they provide a background for negotiations and communiques. Ultimately the nuclear energy forecasts are published in the Annual Report to Congress (9) in the private sector the forecasts are used throughout the power industry. For example, the Atomic Industrial Forum currently uses EIA's nuclear fuel cycle demand forecasts in their annual report (3). The forecasts are also submitted as part of an active participation with international organizations such as OECD's Nuclear Energy Agency and the Nuclear Subgroup of the International Energy Agency.

Because of the importance of these forecasts the Office of Validation Analysis of the EIA has contracted with the Model Evaluation Team of the Oak Ridge National Laboratory (ORNL) to validate a nuclear fuel cycle model code that is presently used, or has potential for

use, by the Nuclear Energy Analysis Division. This report is the result of the first step in this validation effort.

By the term "validation" we mean a complete review and assessment of the underlying economic assumptions of the model, the associated mathematical algorithms, the data base, the documentation, and other factors pertinent to the predictive capability of the model code. Weisbin, Peelle, and Loeb1 (36) have recently described such an approach to comprehensive evaluation.

The purpose of this report is twofold. First, the report describes the results of a brief survey of existing computer codes which model one or more aspects of a projected nuclear fuel cycle. Second, the report provides specific recommendations for the selection of a model code for validation by the ORNL Model Evaluation Team as well as for possible further development. The survey focused on those codes which are potentially useful to the Nuclear Energy Analysis Division in performing the tasks outlined in its program plan for FY 1981-82 (10). In particular, the code's relation to the development of a comprehensive fuel-cycle analysis system was considered.

The review of the literature on nuclear fuel-cycle codes reveals that the codes may be classified according to the following three types:

- (1) Nuclear fuel-cycle material flow-rate codes compute the flow rates and inventories at particular nodes (separative work, reprocessing, waste disposal, etc.) in the cycle given a specified year-by-year installed capacity. Examples of such codes are NUFUEL (30), FLYER (11), and KWIKPLAN-WASPR (17), (29).

(2) Nuclear-power cost-related codes compute estimates of the cost of producing electrical power and/or of various related component costs. This category may be broken down into the following four subcategories:

(a) Codes for calculating the unit costs of individual fuel-cycle operations (typically \$/kg of heavy metal). Such codes include FABCOST-9 (18) which calculates the fabrication costs of fuel assemblies, MYRA (25) and LMYRA (21), which calculate spent-fuel shipping costs, and TASC0 (27) which calculates the cost of tank storage of high-level waste. Such codes typically calculate a short-term (constant or levelized) unit cost based on some specific plant size.

(b) Reactor fuel-cycle cost codes that calculate the levelized or batchwise fuel-cycle cost of a reactor (typically mils/kwh) and which use as input the unit costs of individual fuel-cycle operations. Such codes are typified by REFCO and POW76 (28). The other major input required by these codes is the reactor mass-balance history over its operating lifetime. Such programs can be used for comparing the costs of alternative fuel cycles for a given reactor, but normally they do not include any formalized optimization procedure.

(c) Fuel-cycle industry simulation codes, such as FUELCO (22), which calculate long-term curves of unit cost vs. time for particular fuel-cycle operations (fabrication, shipping, reprocessing, etc.). FUELCO simulates the growth pattern of the segment of the fuel-cycle industry providing the service in question and calculates the price at a given time based on the costs of the plants operating at that time. Such codes are used in long-term reactor-mix optimization programs such as ALPS (13) and ORSAC (37). EUREKA (8) serves a similar function for the uranium-mining and -milling industry.

(d) Other codes which are related to the calculation of components of power cost other than fuel-cycle cost. Such codes include ORCOST (5) and CONCEPT (14) which estimate capital costs, and OMCOST (20) which estimates operating and maintenance costs. The POWERCO code (23) should be mentioned in this category.

(3) System optimization codes produce forecasts based on optimization of growth patterns and power-plant mix according to a prescribed objective function such as minimum total cost and

subject to political, regulatory, safety, and other constraints. A linear-programming module is typically a component of these codes. Examples of optimization codes are ALPS (13), ORSAC (37), and ORSIM (3).

Appendix A categorizes the codes most used at Oak Ridge according to the above classification scheme.

In addition to classifying the codes according to the above scheme (which is based on a nested set rather than a set of mutually exclusive classes), consideration was given to other code characteristics. What are the exogenous or input variables? What variables does the code forecast? Is the code long-term or short-term, domestic or international, regional or nationally aggregated? Does it handle the front-end or back-end of the fuel cycle? What types of reactors does it consider? Other important items addressed include the funding agency, the author and his organization, the date of completion of the code, adequacy of documentation, computer requirements, and a history of use.

Although this survey was brief (completed in two months) and hence necessarily restricted in scope, nearly thirty codes were found and reviewed. Fifteen of these codes have been identified as potentially useful in fulfilling the tasks of the Nuclear Energy Analysis Division as defined in their FY 1981-1982 Program Plan (9). Each of these fifteen codes is described in Appendix B. For illustrative and other purposes, six codes which span typical nuclear fuel cycle activities have been selected for more detailed review. These six are given individual reviews in Section II.



On the basis of the survey and the summaries presented in Section II and Appendices A and B, recommendations are made in Section III for selecting a nuclear fuel-cycle code of interest to the Nuclear Energy Analysis Division for validation.

#### SECTION II: SELECTED REVIEW OF FUEL-CYCLE MODEL CODES

This section of the report reviews in more detail six of the nuclear fuel cycle codes surveyed in this report. ALPS, EUREKA, FLYER, NUFUEL, SFLM, and SNAPPS were chosen for more detailed review for a variety of reasons, including availability of information (documentation, user's guides, etc.), current usage, and apparent interest by EIA. Undoubtedly many more codes could have been reviewed in detail if the time allotment for the report had been greater. Table I summarizes the information presented in this section.

##### ALPS — A Linear Programming System

ALPS is a linear program system which forecasts an optimum growth pattern of fossil and nuclear electric power plants. ALPS was originally developed in 1972 for the Atomic Energy Commission (AEC) by the Hanford Engineering Development Laboratory (HEDL) and has been regularly modified since then for ERDA by HEDL. ALPS has been used in numerous planning and cost-benefit studies for the AEC and for ERDA.

The ALPS model is a system of three subcodes: the MAJOR matrix generator code, any generalized linear-programming (LP) code, and the SCRIBE report-writer code. MAJOR reads input from either cards or tape, computes the matrix coefficients, and writes the coefficients in LP compatible format. The LP code then computes the optimal solution which is then input into SCRIBE. The report-writer code prints

TABLE I: Summary of Selected Fuel Cycle Codes

CODE	Part of Fuel Cycle Addressed	Code Class	Current Usage	Status	Documentation	Computer Language	Sponsor	Author/Organization
ALPS	Nuclear power production	Optimization Code	A working version at ORNL	Complete	Poor	FORTRAN and any LP Module	HEDL	Hardie, Black, Little (HEDL)
NUFUEL	Original version front-end only. Modified version back-end constraint capability.	Material flow rate code	EIA	Complete	Original version adequate. Modified version poor.	FORTRAN	AEC	Artha Jean Snyder (AEC)
FLYER	Front-end	Material flow rate code	ORGDP	Original version complete. Cost capability in progress.	Poor	FORTRAN	ORGDP	E. H. Gift and W. D. Goode (ORGDP)
SNAPPS	Nuclear power production	Material flow rate code	EIA	Complete	Poor	FORTRAN	EIA	R. Clasen (EIA)
EUREKA	U <sub>3</sub> O <sub>8</sub> mining and milling	Material flow rate code	EIA	Domestic version complete. International version in progress	Poor	FORTRAN	EIA	de Halas, Russell, Furtney (Colorado Nuclear Corp.) D. Jackson (DOE)
SFLM	Spent fuel logistics	Transportation algorithm	ORNL	Complete	Poor	FORTRAN	ORNL	D. S. Joy and B. Holcomb (ORNL)

the optimal solution and other miscellaneous data. ALPS selects the optimal mix of fossil (coal, oil, or gas fueled) and nuclear power plants by minimizing the total discounted costs subject to the constraints imposed by the exogenously determined energy demand, fuel availability (fossil, Pu, and  $^{233}\text{U}$ ), plant availability, maximum buildup rates, and construction rates.

The total cost of a plant is partitioned into the total cost excluding fuel costs, and taxes. Fissile Pu and  $^{233}\text{U}$  are not treated as fuel costs since they are generated and used internally. ALPS calculates  $\text{U}_3\text{O}_8$  costs as a function of  $\text{U}_3\text{O}_8$  consumption. Numerous additional cost parameters are input for each plant. These include such items as salvage value, capital costs, plant life, capital replacement rate, property tax rate, insurance rate, variable operation and maintenance charges, income tax rate, and rate of depreciation (13, pp. 7-12).

Five fuel types are considered in the nuclear fuel cycle itself:  $^{232}\text{Th}$ ,  $^{233}\text{U}$ ,  $^{235}\text{U}$ ,  $^{238}\text{U}$ , and fissile Pu. Any number of fuel cycle schemes may be employed. Hence, ALPS is able to model any type of reactor that can be described using the feed and discharge quantities of the above fuel types (12, p. III-27). A cost is assigned during each stage of the fuel cycle. These costs are determined by input parameters which include tails assay, cost of separative work, conversion, enrichment, fabrication, and reprocessing.

ALPS is similar to the combination of CLOTHO, POWERCO, PACTOLUS, DAEDALUS, LP(BONNER-MOORE), and MERCURY. ALPS differs from these codes (13, p.2) in the following ways:

- i) ALPS is more tightly integrated.
- ii) ALPS allows any number of independent fuel cycle schemes for each plant. This allows a separate treatment of the core and blanket of a breeder, for example.
- iii) In contrast to previous codes, ALPS distinguishes between coal, oil and gas-fueled fossil plants and can treat a mix of fuels.
- iv) ALPS allows for multiple load factor profiles, whereas previous codes allowed only two.

The ALPS code has recently been modified to accommodate up to nine distinct regions or countries (12, p. 111-26). The documentation of ALPS is poor and model modification would require close communication with HEDL (12, p. 111-28). Currently, ALPS employs either the UNIVAC 1108 LP or Hanford LP code (13, p. 2 and C-1). A version of ALPS was run on IBM/91 at ORNL with a local LP module. Although the code has been used extensively by AEC and ERDA, it has not gained general acceptance for projecting fuel cycle requirements. ALPS strength lies principally in its ability to estimate the costs and system planning implications of new nuclear technologies and fuel cycle concepts (12, p. 111-28). Furthermore, ALPS is one of very few codes which employs an optimization routine.

#### EUREKA — Uranium Supply and Market Price Model

The EUREKA code was written for the EIA by D. R. de Halas, G. L. Russell, and M. Furtney (all of the Colorado Nuclear Corporation), and Diane L. Jackson of DOE. EUREKA models the supply and demand relations of the uranium market in order to forecast future uranium

prices, supply, inventories, mining/milling capacity exploration activity, capital expenditures, and import/export levels. These forecasts of uranium industry variables aid the DOE in its efforts to plan uranium enrichment and fabrication activities, to estimate optimal tails assays, to investigate the relative costs of different methods of electricity generation, and to evaluate the economic desirability of breeder reactors (6, p. 109). EUREKA will also serve as the source of exogenous uranium demand inputs to the comprehensive international nuclear fuel-cycle model currently being built under the sponsorship of EIA (2, p. 13). The first version of EUREKA (completion date not available) was a domestic model. In 1978 de Halas began work on developing an international version of EUREKA. This effort is reportedly near completion but out of funding.\*

The EUREKA code is a relatively large code. The input data alone consists of 152 single-valued variables and 17 multi-valued variable arrays (8, p. 1). The input data consists of information on current market price, average market price over the next 10 years, quantity demanded by year, mining/milling capacities and expansion plans for next 4 years, exploration budgets, and total uranium resources (5, p. 112). Once these data are entered, EUREKA performs preliminary calculations such as dividing total uranium deposits into 5 depth groups, 5 grade groups, and 5 size groups (8, p. 1). Then EUREKA proceeds with its annual calculations. First, the code calculates the "economic cost" of each

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\*Source: Conversations with Gene Clark, Nuclear Energy Analysis Division, EIA, and with D. de Halas.

uranium deposit and compares the cost per ton to current market price per ton to decide whether to begin developing the property. Next the code reviews mine capacities and modifies them according to changes in existing uranium prices. Then EUREKA computes excess production capacity or excess demand for the current period. The market price for the next calculation year is completed using a nonlinear equation which depends, in part, upon the differences between "unfilled demand" and "unsold capacity" (6, p. 115). Finally, EUREKA calculates exploration activities based on future consumption requirements and existing capacity. The major part of the EUREKA output is presented in a summary table which includes the following projections for each year:  $U_3O_8$  price, average price, inventory (tons  $U_3O_8$ ), ore stockpile (tons  $U_3O_8$ ), shortfall (tons  $U_3O_8$ ), capital expenditures (millions of dollars), average grade (per cent), mill and mine capacity (ton  $U_3O_8$ /year), demand (tons  $U_3O_8$ /year), imports and exports. (8, pp. B1-B14).

The EUREKA code is a fast-running FORTRAN IV program (8, p. 14). Its average run time is approximately proportional to the number of years being forecast. A twenty-five year projection requires about 100 cpu seconds on a CDC Cyber 70 Computer (8, p. 14). Although EUREKA remains poorly documented, at least for non-purchasers of the code, a user's guide (8) and code listing are available as well as an extensive economic evaluation by Charles River Associates, Incorporated (CRA).

The CRA report on EUREKA identifies seven problem areas. These problems may be summarized briefly as follows (6, pp. 123-131):

1. EUREKA does not guarantee market clearing behavior.

Uranium production does not necessarily equal the exogenously

determined demand. No foreign section is included to take up the "slack" through imports or exports.

2. The uranium producers' decisions are based on previous prices rather than on expectations of future prices. This behavior leads to cyclical price forecasts which would not occur when decisions are made using rational formation of expected future prices.
3. EUREKA requires large amounts of specific information about mines and deposits, but fails to employ it.
4. Mines and deposits are not exploited in a sequence reflecting increasing extraction costs.
5. Uranium production decisions are based upon cash-flow considerations rather than profit maximization. In the presence of efficient capital markets, cash-flow decision-making is seen as irrational by economists.
6. EUREKA employs user adjusted behavioral relationships rather than estimating the functional forms from real world data.
7. EUREKA employs "psychological" variables in the behavioral equations which in reality are unobservable.

In response to the CRA criticism, de Halas defended the EUREKA code on the following major points (7):

1. The lack of market clearing in the EUREKA code was intentional. The domestic scope of EUREKA requires surpluses and shortages to account for imports and exports. In de Halas' new international code, markets are designed to clear.

2. De Halas assumes the investor (uranium deposit owner) develops those deposits which satisfy investor criteria concerning future uranium prices and risk considerations. The fact that other investors are bringing cheaper property into production is of no concern. The owners are neither cost-minimizers nor profit-maximizers.
3. De Halas rejects the argument that production costs play a role in the determination of uranium prices. He favors the less restrictive notion that if uranium is abundant, price falls and if scarce, price rises.
4. De Halas argues that uranium producers' behavior is, in fact, myopic. According to de Halas, buyers and sellers make no judgment as to expected future prices relying instead upon current price information only.
5. The EUREKA code lacks empirical content because some factors cannot be quantified from existing data.

Numerous additional minor points are addressed in the de Halas rebuttal to CRA.

#### FLYER — Fuel Cycle Requirements

The Operations Analysis and Planning group at the Oak Ridge Gaseous Diffusion Plant (ORGDP) developed FLYER to provide analyses similar to the NUFUEL code which was not available for general use in 1976 (11,p. 3). FLYER is designed to permit comprehensive yet flexible analysis of the nuclear fuel cycle. Using long-run forecasts (75 years) of nuclear power growth and given converter reactor growth rate mixes, uranium and separative work requirements may be investigated for a large number of fuel cycle scenarios. In particular the



code investigates the long-run effects of nuclear fuel cycle options such as reactor type choice, fuel cycle changes and improvements, uranium and plutonium recycle, reprocessing and mixed fabrication limitations, and systematic delays between fuel cycle stages. The FLYER output consists of a comprehensive breakdown of the uranium and plutonium mass flows both annually and cumulatively. Unlike some other codes it does not compute costs, just quantities. FLYER is a deterministic model rather than one which optimizes fuel use or nuclear growth.

FLYER has the flexibility to handle four reactor types — PWR, BWR, HTGR, and FBR. In addition five levels of breeder technology are provided. The mix of converter type reactors is specified yearly whereas breeder capacity is determined by build-rate limitations and plutonium and MOX fabrication capacity (11, p. 5). Plutonium recycle is permitted, but it is limited to the amount of plutonium remaining after breeder requirements have been met (12, p. III-26). Separate constraints on reprocessing and MOX fabrication can be specified for converters and breeders. Separative work may be constrained so that nuclear growth is limited endogenously given a tails assay. Alternatively, the tails assay may be allowed to adjust for a given rate of nuclear growth (12, p. III-26).

Although FLYER performs analyses similar to NUFUEL, FLYER has two additional features not available in NUFUEL. Uranium requirements are calculated for the entire lifetime of a particular reactor, and these uranium requirements are cumulated over time to reflect their respective uranium commitments. Interaction in the back-end of the fuel

cycle is handled separately so that the impact of limited reprocessing and MOX fabrication may be investigated (11,p. 3). In contrast to NUFUEL, FLYER seems incapable of regional analysis.

FLYER is used extensively by ORGDP for internal planning studies (11,p. 5). The code is particularly useful in front-end studies that investigate the effects of nuclear growth on uranium and separative work requirements. FLYER's main shortcomings include its lack of regional capability, poor documentation, and lack of cost capability (12,p. 111-26). Currently, an effort is being made to add cost capability. No reference was found regarding the computer requirements of FLYER.

#### NUFUEL

The NUFUEL code was created in 1974 by Artha Jean Snyder to calculate the annual requirements for separative work and uranium for the Atomic Energy Commission's forecast of nuclear power growth and enrichment (30). NUFUEL has recently been revised (1978) by Battelle Pacific Northwest Laboratories (PNL) through the funding of DOE (then FEA) under the leadership of D. E. Doenigi (12, p. 111-6).

NUFUEL is one of a family of six codes (GFPF, SELECT, NUFUEL, NUPLANT, NUCOST, and NUEN) dealing with the nuclear fuel cycle (12, p. 111-7). The six codes may be run separately or as a unit depending on the user's particular needs. The general purpose forecasting program GFPF forecasts installed-capacity schedules for nuclear plants of different types by region. Then, SELECT collects certain data from GFPF's output to use as input into NUFUEL. NUFUEL serves as the system's principal accounting module and computes fuel process

flow rates and material requirements. The set of flow rates and inventories at each node in the cycle is calculated by NUPLANT. NUCOST generates cash flows and levelized fuel cycle costs using either exogenous unit prices or endogenously determined material and service costs. NUEN calculates the various types of fuel cycle effluents. These estimates can be used to calculate environmental effects of the nuclear fuel cycle.

Although NUFUEL originally emphasized front-end features of the fuel cycle, in its modified form it can handle back-end fuel cycle additions or constraints easily (12, 111-9). The NUFUEL code currently handles PWR, BWR, HTGR, early LMFBR, and advanced LMFBR fuel cycles. Accommodation of light water or fast breeder reactors using thorium would require significant modification of the code (12, p. 111-9). NUFUEL has the flexibility to recycle both uranium and plutonium. Plutonium is recycled to these reactors with the highest level of plutonium capability on a preferential basis up to an exogenously specified limit. The SELECT module allows the NUFUEL code to handle regional analysis. The regional capability may be extended to international analyses as well (12, p. 111-10).

NUFUEL is a FORTRAN code (GPF is COBOL) designed to run on CDC-6600/7600 computers. Storage is not considered a problem (12, p. 111-11). "A typical NUFUEL case might require on the order of one to two minutes of CPU time" (12, p. 111-11). The original version of NUFUEL is considered to be adequately documented. However, the modified version's documentation is incomplete. The major drawback of NUFUEL is its difficulty of use. It requires a large investment of time to

become adequately familiar with the code to understand its operation and to correctly employ its numerous options (12, p. 111-21). NUFUEL is presently being used by Gene Clark at the EIA.

#### SFLM — Spent Fuel Logistics Model

SFLM was developed in 1978 by D. S. Joy and B. Holcomb of Oak Ridge National Laboratory (ORNL) to evaluate the effect of waste management policy on the transportation requirements for moving spent fuel from reactors to alternative away-from-reactor (AFR) storage facilities and ultimately to permanent geological repositories. Funding for SFLM came from the DOE through the Transportation Technology Center (TTC) at Sandia National Laboratories (16, p. 1). The model has been regularly updated by ORNL.\* SFLM has been used by DOE, the TTC, the Office of Nuclear Waste Isolation (ONWI), and the Savannah River Laboratory (SRL) (16, p. 4). SFLM is considered to be a more comprehensive model than DISFUL, a similar code developed by the Stoller Corporation, SRL, and funded by DOE.

The SFLM code is a mathematical formulation for solving the transportation problem of intermediate storage (AFR) and/or subsequent transportation to a federal repository (long-term storage and/or disposal). A linear programming technique is employed to minimize the total cost of shipping spent fuel either to an AFR and finally to a repository or initially to a repository bypassing AFR storage. SFLM is capable of handling 30 generating sources, 10 AFR's, and 10 federal repositories over a study period of 80 years (16, p. 1). In order to capture the operational characteristics of the AFR's, repositories, and transportation system, SFLM employs the following constraints (16, p. 22):

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\*Source: Conversation with D. Joy, ORNL.

- (1) storage capacity at generation site,
- (2) storage capacity at AFR's,
- (3) storage capacity at repositories,
- (4) fuel receiving rates,
- (5) opening and closing dates of various receiving facilities,  
and
- (6) *minimum residence time of spent fuel at repositories.*

The mode of transportation may also be influenced by the user.

The data requirements of SFLM include the dimensions of the transportation problem (number of generating sites, AFR's, repositories, and number of years), amount of spent fuel added to storage pools annually, maximum capacity of storage pools, amount of spent fuel initially stored, maximum AFR storage capacity, minimum required AFR storage time, cost of waste loading, cost of waste unloading, shipping cost, and storage cost (15, p. 26). The output of SFLM supplies the following information (16, p. 4):

- (1) a schedule and destination for all shipments,
- (2) inventories of fuel at reactors, AFR's and repositories,
- (3) transportation distance and cost,
- (4) radiation exposure to the public,
- (5) cask fleet requirements,
- (6) ratio of rail and truck shipments, and
- (7) the age distribution of shipped or stored fuel.

No users' guide for SFLM has been prepared. As a result, documentation is incomplete. The computer requirements for SFLM are unknown at this time. The people to contact for more information regarding SFLM are Larry Shappert and David Joy of ORNL.

### SNAPPS — Short-Term Nuclear Annual Power Production Simulator

SNAPPS was developed by a mathematician named Rich Clasen in 1978 under the sponsorship of the EIA.\* SNAPPS computes the supply of energy produced by domestic nuclear reactors during the period 1979-1983. In order to determine individual reactor power curves, the code requires input data on thermal power rating, scheduled outages, start-up time, full-power days, capacity factor, refueling time, and reactor construction time (33, p. 1). Capacity factors, refueling times, and reactor construction times are treated as random variables in order to inject uncertainty into the production of nuclear power supply (19, p. 1). SNAPPS output consists of nuclear power in each year (1979-1983) in millions of kilowatt hours, region number, month and year of start-up date, percent completion, and the standard deviation of output for each domestic reactor. The code also calculates nuclear power output by region and outputs ten regional power supplies as well as the respective standard deviations (35, p. 2).

As noted above, SNAPPS provides a regionalized short-term, domestic code to forecast the nuclear power production segment of the nuclear fuel cycle. It deals only with PWR and BWR reactors. A complete economic evaluation of the SNAPPS code may be found in "Economic Evaluation of the Short-Term Nuclear Power Production Simulator (SNAPPS) Model" (31). The evaluation concludes that although SNAPPS contains no

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\*Rich Clasen died shortly after the completion of SNAPPS (32, p. 1). Gene Clark is currently the best source of additional information on this code.

economic structure, its predictive power is unimpaired as long as the forecast period is short enough so that changes in the omitted economic variables do not have time to affect power production. SNAPPS is currently being used very successfully by Gene Clark to predict nuclear power production six to eight quarters into the future. The documentation of SNAPPS is incomplete. The complete FORTRAN code is available, but no complete list of all variables, equations, constraints, and definitions is available yet. SNAPPS can be run on computer facilities capable of handling FORTRAN.

### SECTION III: RECOMMENDATION

This recommendation section consists of two parts. The first part of this section matches each of the four program areas outlined in the NEAD program plan (10) with the fuel-cycle codes which may satisfy the requirements of each program area. The second part recommends one of the nuclear fuel-cycle codes for evaluation by the ORNL model-evaluation team.

The NEAD program plan includes four program areas: 1) nuclear power, 2) nuclear fuel demand, 3) nuclear fuel-processing supply, and 4) uranium supply. The nuclear-power area covers the forecasting of nuclear-power capacity, analysis of nuclear power plant construction, operating and decommissioning costs, and the development of new technology for nuclear power use. For short-term forecasts of nuclear power, SNAPPS is probably adequate. For longer range forecasts no currently available code is fully satisfactory. Further development of

Andress' code (2) is probably required. No currently available methodology can be recommended with confidence. CONCEPT and OMCOST may be useful in forecasting construction and operation costs.

The nuclear fuel demand area deals with the translation of nuclear energy demand (derived from electricity demand) into demand for uranium and nuclear fuel processing services. Codes surveyed in this report which may be useful to NEAD in this area include NUFUEL, KWIKPLAN, FLYER, CLOTHO, and NUFACTS. It is recommended that the methodologies of these codes be compared and evaluated to select the most appropriate one for NEAD use.

The area of nuclear fuel processing supply involves determining the expected price and output for world-wide nuclear fuel processing under various demand and policy scenarios. The supply of enrichment services and nuclear waste services are the major sub-areas of concern to NEAD. Considerable work has been done at Oak Ridge on nuclear waste processing supply and demand. The Oak Ridge codes WASPR and SFLM address the problem of waste storage and transportation. The DISFUL code, which was developed by Stoller Corporation, also models transportation and storage of spent fuel. Again it is recommended that the methodologies of these codes be compared and evaluated to determine their relative merits for employment by NEAD.

The uranium supply area forecasts uranium supply, and assesses the domestic uranium resource base. In spite of CRA's criticisms, EUREKA remains the most suitable code for forecasting the supply of uranium and addressing related questions. EUREKA will also provide uranium supply information in the Andress international fuel cycle



model. Therefore, it seems imperative that an evaluation of the EUREKA code be undertaken.

After reviewing the information on NFC models obtained over the past two months and the discussion of November 21, 1980, with G. Clark J. Finucane and D. Andress, the authors of this report come to the conclusion that the most efficient use of their time for the remainder of FY81 would be to perform a complete validation of the code EUREKA, as presently used by the NEAD (Version NEAD 10/10/79).

Clearly it would be desirable to validate a code presently used at NEAD and which hopefully will continue to be used at NEAD, particularly to generate numbers used in the ARC. The authors understand that three NFC codes are presently in use at NEAD: EUREKA, NUFUEL, and SNAPPS. Gene Clark, director of NEAD, hopes to replace NUFUEL and SNAPPS with the new "Nuclear Fuel-Cycle Optimization Model" presently designed by D. Andress as soon as sufficient funding will allow Andress to complete this code. In addition, SNAPPS has insufficient economics and mathematics to be interesting for validation. NUFUEL is much used and accepted by DOE; it would be of interest to compare in detail NUFUEL with the Oak Ridge codes FLYER and KWIKPLAN which solve nearly the same problem. But such a comparison should probably not be done by an Oak Ridge team, which may lack "credibility" in recommending Oak Ridge codes. EUREKA is probably the only current code which models in detail the uranium supply and market conditions, hence it is likely that NEAD will continue to use it. Furthermore, D. Andress is planning to incorporate EUREKA in his model. Therefore, a validation of EUREKA should be valuable for NEAD and for OEIV.

## ACKNOWLEDGEMENTS

Much of the information presented in this survey was obtained through discussions with specialists in the field, particularly in the Oak Ridge area. We are grateful for the very useful guidance provided by C. W. Alexander, A. G. Croff, D. S. Joy, L. R. Shappert of the ORNL Chemical Technology Division; J. G. Delene, Engineering Technology Division, A. M. Perry, Energy Division, T. J. Burns and J. P. Renier, Engineering Physics Division and E. H. Gift and B. E. Prince of the Operations Analysis and Planning Division of the Oak Ridge Gaseous Diffusion Plant. We are especially thankful for the careful reading of the manuscript by R. Salmon and for his extensive and useful comments.

We have also obtained very valuable information from G. Clark, (NEAD) J. Finucane, (OEIV), O. Ozer, (EPRI) and J. J. Staggs (DOE, Resource Application).

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## APPENDIX A

OVERVIEW OF NUCLEAR FUEL-CYCLE CODES  
USED AT OAK RIDGE

Much of the information developed for this survey was obtained from discussions with individuals involved in some aspect of the nuclear fuel cycle in the Oak Ridge area. These individuals use mostly codes which they or their colleagues have developed at one of the Oak Ridge area installations. This appendix is a short overview of the codes which appear to be most used at Oak Ridge; the codes are grouped in three categories according to whether they are mostly used for modeling fuel and fuel services flow rates, for computing fuel costs and associated power-generation costs or for optimizing some cost related objective function.

1. Nuclear Fuel and Fuel Services Flow Rates Codes

The two codes, FLYER and KWIKPLAN, were developed independently at about the same time (1976), and are still used and occasionally modified and improved. When these codes were written the AEC code NUFUEL was not available for use at ORNL.

FLYER was developed by "Operations Analysis and Planning" initially to provide information on uranium feed and separative work requirements for the Oak Ridge Gaseous Diffusion Plant. The code underwent several modifications and improvements. Presently it includes no cost information, but work is in progress to increase the capability of FLYER mostly to predict total investment costs in different nuclear fuel cycle operations. (p.c. from E. Gift)

KWIKPLAN was developed by the Chemical Technology Division of ORNL to project annual requirements of fuel cycle operations. The output of KWIKPLAN can be used by WASPR, a waste projection code also written by ORNL Chemical Technology Division. WASPR incorporates some of the routines of ORIGEN (4), an elaborate isotope generation and depletion code, to generate isotopic decay information with the waste projection. The ORNL Chem. Tech. Division is presently actively involved in a projection of waste management costs; this effort includes the development of new modeling codes. The code SFLM, also prepared by ORNL Chem. Tech. Division, models the transportation of radioactive waste and spent fuel.

## 2. Nuclear Fuel-Cycle-Cost Codes

Two main lines of cost codes are maintained at Oak Ridge:

a) Royes Salmon has developed POWERCO (23,24), REFCO (28), POW76 (28), and FUELCO, a series of codes to compute unit process costs, costs as a function of time, levelized costs, etc. These codes were used extensively for the Reactor Fuel Costs Study of 1966-70 (Reactor Fuel Cycle costs for Nuclear Power Evaluation, WASH-1099), and more recently for the NASAP and AFCEP studies. Parts of these codes have also been incorporated into optimization codes such as ALPS at HEDL, ORSAC at ORNL, and LPC at LASL. The documentation of the presently used version of this system of codes is poor. b) The Engineering Technology Division of ORNL has written several codes to estimate costs of capital and operation and maintenance of nuclear and fossil fuel power plants: CONCEPT-5, OMCOST, ORCOST-2. These codes are actively used, frequently

updated and fairly well documented. The codes are based on detailed itemized lists of construction, equipment and maintenance costs, which include regional escalation cost indices for each category.

### 3. Optimization Code

ORSAC is apparently the only full nuclear fuel cycle optimization code assembled at Oak Ridge. It was written in the early 1970's to optimize a power plant combination to provide a given U.S. electric capacity at minimum cost. ORSAC uses routines from FUELCO to compute unit process costs, and from POWERCO to process reactor costs. A Linear Program Module minimizes an objective function subject to given constraints.

ORSAC is similar to ALPS, written at HEDL; ORSAC is no longer used at ORNL mostly because this kind of optimization study is no longer performed at ORNL. ALPS has been kept more up-to-date and hence should be preferred.

Another optimization-type code, ORISM (34), was developed at ORNL in collaboration with TVA and Commonwealth Edison. It attempts to minimize the total discounted operating cost over a specified period, given a forecast for future power loads. The optimization is done by a probabilistic simulation approach.



APPENDIX B

SUMMARY OF RECENT NUCLEAR FUEL CYCLE CODES

Table B-I lists 15 nuclear fuel cycle codes which have been identified as potentially useful to address tasks of the Nuclear Energy Analysis Division as defined in the FY 1981-1982 Program Plan.

The table is followed by a brief abstract of each of the codes, as given in the code's user's guide or other relevant reference. The number, title and authors of the reference are given above the abstract.

Except for ORSAC and ORSIM, all of the codes are still used and occasionally revised. Sometimes the latest version incorporates substantial improvements over the version described by the abstract.

Except for NUFACTS all of the codes have been operated at ORNL on ORNL computers.

TABLE B-I. Codes Related to Nuclear Power Costs

Code Name	Year	Main Application
ALPS (1)	1972	Optimizes fossil and nuclear power growth pattern
CONCEPT-5	1979	Estimates capital costs: fossil and nuclear power plants
DISFUL	1979	Models transportation and storage of spent fuel
EUREKA	1980	Examines supply and demand in uranium market
FLYER	1976	Analyzes nuclear fuel and fuel services requirements
KWIKPLAN (2)	1977	Analyzes nuclear fuel and fuel services requirements
NUFACTS	1978	Simulates nuclear fuel cycle activities
NUFUEL	1974	Analyzes nuclear fuel and fuel services requirements
OMCOST	1979	Estimates nonfuel operating and maintenance costs: electric power plants
ORSAC (1)	1971	Optimizes fossil and nuclear power growth pattern
ORSIM	1975	Minimizes total operating cost of power generating system
REFCO (1)	1971	Computes unit fuel costs for power generation
SFLM	1978	Models transportation of wastes and spent fuel
SNAPPS	1978	Simulates short-range energy supply (1979-1983)
WASPR (2)	1978	Projects volumes and composition of nuclear wastes

Notes

- (1) The codes POWERCO, REFCO, POW76 and FUELCO (all developed by Royes Salmon) compute power costs, fuel-cycle costs, and the unit costs of fuel-cycle operations. ALPS and ORSAC incorporate parts of these codes with a Linear Programming module.
- (2) WASPR was designed to use input mass-flow data as obtained from KWIKPLAN.

ALPS

HEDL-TME-7231 (1972)

ALPS, A LINEAR PROGRAMMING SYSTEM FOR FORECASTING  
OPTIMUM POWER GROWTH PATTERNS

R. W. Hardie, W. E. Black and W. W. Little  
(Hanford Engineering Development Laboratory)

This report describes the linear programming system, ALPS, which predicts the optimum growth pattern in a mix of fossil and nuclear power plants. Plants are selected to minimize the total discounted costs while satisfying constraints on energy demand, fuel availability, introduction dates, and construction rates. The ALPS model consists of the MAJOR matrix generator code, any generalized LP code, and the SCRIBE report writer code. ALPS is similar to the POWERCO, PACTOLUS, DAEDALUS, CLOTHO, LP (BONNER-MOORE), and MERCURY code series, used in previous AEC LMFBR Cost/Benefit Studies, but was designed to be machine independent and more compact.

CONCEPT-5

ORNL-5470 (1979)

CONCEPT-5 USER'S MANUAL

C. R. Hudson, II  
(Oak Ridge National Laboratory)

The CONCEPT computer code package was developed to provide conceptual capital cost estimates for nuclear-fueled and fossil-fired power plants. Cost estimates can be made as a function of plant type, size, location, and date of initial operation. The output includes a detailed breakdown of the estimate into direct and indirect costs similar to the accounting system described in document NUS-531.

Cost models are currently provided in CONCEPT-5 for single- and multiunit pressurized-water reactors, boiling-water reactors, and coal-fired plants with and without flue gas desulfurization equipment.

DISFUL

From an Exhibit, March 22, 1979  
(The S. M. Stoller Corporation)

- Calculates, for Spent Fuel
  - Reactor Pool Status
  - Discharge Quantities
  - Off-Site Storage Requirements
  - Shipping Cask Requirements
  - Tonne-Miles Shipped
  
- Calculation Basis
  - Detailed Data Base
  - Options for Pool Capacity Expansion
  - Options for Defining Off-Site Shipment Requirement
  - Options for Trans-Shipment Scenarios
  - Options for Calculation of Nominal Discharge Size
  
- Edits
  - Graphic and Tabular
  - Options for Level of Detail Required

EUREKA

EUREKA User's Guide (1980)

D. R. de Halas, G. L. Russell, M. Furtney  
(Colorado Nuclear Corporation)

D. L. Jackson  
(Department of Energy)

EUREKA examines the supply/demand situation in the uranium market with a year-by-year calculation. Using an initial data fit to recent DOE estimates of uranium reserves, EUREKA classifies the reserve inventory into 75 groups (5 depths, 5 grades and 3 sizes) and evaluates the cost at which production would be profitable for each group of reserves. After comparing this cost with current market price, a decision is made about putting an individual reserve group into production to meet future uranium needs. Adjustments are then made to production levels from existing reserves to accommodate the changing economics. The short-range supply/demand situation is analyzed, and the price for the next year is determined. This price is used to justify future production. Exploration activities are then defined based on need, current status of reserves, and available cash. These calculations are then repeated for the next year.

FLYER

K-OP-187 (1976)

SUMMARY REPORT: FUEL CYCLE REQUIREMENTS CODE (FLYER)

E. H. Gift and W. D. Goode  
(Oak Ridge Gaseous Diffusion Plant)

A code, the Fuel Cycle Requirements Code (FLYER), is available to analyze the impact on nuclear fuel and on related industrial demands of foreseeable uncertainties in nuclear power growth, reactor type availability, plutonium recycle, and reprocessing and mixed oxide fabrication availability. The model has proven to be a useful tool for sensitivity studies of impacts of various nuclear power growth and fuel cycle contingencies. Using long term (up to 75 yr) projections of total nuclear power growth and specified fractional relationships among converter (PWR, BWR and HTGR) reactor growth rates, the nuclear fuel and separative work requirements may be computed for a large number of fuel cycle scenarios. The model is deterministic and no optimization of fuel use or nuclear growth is made.

KWIKPLAN

ORNL/TM-5880 (1977)

KWIKPLAN — A COMPUTER PROGRAM FOR PROJECTING THE ANNUAL  
REQUIREMENTS OF NUCLEAR FUEL CYCLE OPERATIONS

Royes Salmon  
C. W. Kee  
(Oak Ridge National Laboratory)

The computer code KWIKPLAN was written to facilitate the calculation of projected nuclear-fuel cycle activities. Using given projections of power generation, the code calculates annual requirements for fuel fabrication, fuel reprocessing, uranium mining, and plutonium use and production. The code uses installed capacity projections and mass flow data for six types of reactors to calculate projected fuel cycle activities and inventories. It calculates fissile uranium and plutonium flows and inventories after allowing for an economy with limited reprocessing capacity and a backlog of unreprocessed fuel. All calculations are made on a quarterly basis; printed and punched output of the projected fuel cycle activities are made on an annual basis. Since the punched information is used in another code to determine waste inventories, the code punches a table from which the effective average burnup can be calculated for the fuel being reprocessed.



## NUFACTS

TID-29052 (1978)

NUFACTS — Nuclear Fuel Cycle Activity Simulator:  
Reference ManualM. B. Triplett, J. D. Waddell and T. A. Breese  
(Battelle Columbus Laboratories)

The Nuclear Fuel Cycle Activity Simulator (NUFACTS) is a package of FORTRAN subroutines which facilitate the simulation of a diversity of nuclear power growth scenarios. An approach to modeling the nuclear fuel cycle has been developed that is highly adaptive and capable of addressing a variety of problems. Being a simulation model rather than an optimization model, NUFACTS mimics the events and processes that are characteristic of the nuclear fuel cycle. This approach enables the model user to grasp the modeling approach rather quickly. Descriptions of the model and its components are provided with several emphases. First, a discussion of the modeling approach and basic assumptions is provided. Next, instructions are provided for generating data, inputting the data properly, and running the code. Finally, detailed descriptions of individual program elements are given as an aid to modifying and extending the present capabilities.

NUFUEL

WASH-1348 (1974)

COMPUTER PROGRAM NUFUEL FOR FORECASTING  
NUCLEAR FUEL REQUIREMENTS AND RELATED QUANTITIES

Artha Jean Snyder  
(USAEC)

This report describes in detail the computer program which is used to calculate the annual requirements for separative work and uranium which accompany the AEC's periodic forecast of nuclear power growth. Calculations assume that uranium enrichment plants approximate ideal cascade conditions. Plutonium production and requirements and demands for  $UF_6$  conversion, fuel element fabrication, and spent fuel reprocessing are also considered. Input to the program is a schedule of nuclear power plant additions by reactor type. Reactor characteristics and fuel cycle data for each reactor or each type of reactor are also used as input. The report contains descriptions of the methods of calculation contained in the program, of the data sets needed to run the program, of the printed output, and of the options available. Included are listings of the source deck, a set of control cards, and the data sets for a sample case. The output for the sample case and input for several reactor types are also included.

OMCOST

ORNL/TM-6467 (1979)

A PROCEDURE FOR ESTIMATING NONFUEL OPERATION AND MAINTENANCE  
COSTS FOR LARGE STEAM-ELECTRIC POWER PLANTS

M. L. Myers and L. C. Fuller  
(Oak Ridge National Laboratory)

This report presents revised and updated guidelines for estimating annual nonfuel operation and maintenance costs for large light-water reactor and coal-fired steam-electric power plants, which were presented previously in the publication ERDA 76-37 "A Procedure for Estimating Nonfuel Operating and Maintenance Costs for Large Steam-Electric Power Plants" published in October 1975. Estimates for coal plants include the option of limestone slurry scrubbing for flue gas desulfurization. A computer program, OMCOST, based on this procedure is also presented.

ORSAC

ORNL/TM-3223 (1971)

THE OAK RIDGE SYSTEMS ANALYSIS CODE (ORSAC)  
USERS' MANUAL

F. G. Welfare  
O. L. Culberson (Consultant)  
R. C. Durfee  
E. H. Gift  
S. C. Jacobs  
J. P. Nichols  
R. Salmon

(Oak Ridge National Laboratory)

ORSAC consists of a combination of SYSCO, a code developed at Oak Ridge National Laboratory, and MPS/360, an IBM-developed mathematical programming package. These codes, used together, allow the calculation of the combination of power plants which will provide a given electrical capacity in the United States at the minimum cost. Intermediate results include the economic and fuel utilization characteristics of each nuclear or fossil plant type being considered in the system.

This report, while containing a full description of the ORSAC code, is intended primarily as a users' manual. An abbreviated functional description of the code is contained in ORNL-4656, which may be preferred by readers not interested in detailed instructions on use of the code.

ORSIM

ORNL/TM-4506 (1975)

THE OAK RIDGE SYSTEM INTEGRATION MODEL (ORSIM)  
FOR OPTIMIZATION OF UTILITY GENERATION PLANNING

J. C. Turnage, B. E. Prince, D. J. Joy and L. Bennett  
(Oak Ridge National Laboratory)

An electric power generating system integration model has been developed which simulates the multi-year operation of a mixed power system consisting of fossil, nuclear, hydro, and pumped-storage units. This model has been given the name ORSIM, an acronym derived from Oak Ridge System Integration Model. For any specified refueling schedule for nuclear units and forecast of future load, the model determines a plan of operation for the system which attempts to minimize the total discounted operating cost over a specified study period.

The analysis considers the effects of forced outages, spinning reserve operating constraints, and scheduled introduction and retirement of generating stations. The model determines a maintenance schedule for the nonnuclear stations (nuclear stations are maintained during refueling outages) and the optimum allocation of energy-fixed nuclear and hydro resources. It calculates the expected energy generated by each station in the system, period by period over the planning horizon, based on input or calculated incremental operating cost. It also calculates

the expected loss-of-load probability and unserved energy demand for each period in the planning horizon. An optimum operating plan, designed to minimize the discounted total production cost, is then calculated, as are the cost of operating each station in the system and the discounted total production cost for the derived plan of operation.

B-15

REFCO

ORNL-4695 (1971)

TWO COMPUTER CODES (REFCO AND POW76) FOR CALCULATING THE  
FUEL CYCLE COST OF A NUCLEAR POWER REACTOR

Royes Salmon  
(Oak Ridge National Laboratory)

The computer codes described in this report are an outgrowth of the POWERCO code, described in ORNL-3944 and ORNL-4116. All three codes use the discounted cash flow method for calculating levelized costs. In POWERCO, this method was used to calculate the levelized power cost, and subsequently to determine the four components of power cost, representing the contributions of plant capital, nonfuel working capital, fuel cycle cost, and operating and maintenance expense. REFCO and POW76 are designed to calculate the third of these components, the fuel cycle cost.

Both codes were developed from the discounted cash flow equation for fuel cycle cost given in ORNL-4116. The interest rate used for discounting is the weighted average interest rate on debt and equity, adjusted downward to account for the income tax deduction due to bond interest. In POW76, the discounting procedure is based on discrete time periods, typically one month in length. Cash expenditures and incomes are assigned to the end of the month in which they occur.

REFCO uses continuous discounting, so that each expenditure or income is discounted from the precise time at which it occurs. Because of the slight loss of precision inherent in discrete discounting, REFCO is superior to POW76 for the evaluation of small changes in the timing of fuel cycle events. Another advantage of REFCO is that fuel cycle costs are calculated for each batch of fuel both individually and cumulatively through each batch. Also, tax deductible fuel expense can be calculated on a batchwise basis in REFCO, in keeping with present industry practice. REFCO also has provision for parametric studies of the effect of price escalation.

REFCO can also be used to calculate the "equilibrium" fuel cycle cost of a reactor by supplying input data for a single equilibrium batch.

FORTTRAN listings of both codes and the results of example problems are included.



SFLM

ORNL/TM-6192 (1978)

LOGISTICS MODELS FOR THE TRANSPORTATION OF RADIOACTIVE  
WASTE AND SPENT FUEL

D. S. Joy and B. Holcomb  
(Oak Ridge National Laboratory)

Mathematical modeling of the logistics of waste shipment is an effective way to provide input to program planning and long-range waste management. Several logistics models have been developed for use in parametric studies, contingency planning, and management of transportation networks. These models allow the determination of shipping schedules, optimal routes, probable transportation modes, minimal costs, minimal personnel exposure, minimal transportation equipment, etc. Such information will permit OWI to specify waste-receiving rates at various repositories in order to balance work loads, evaluate surge capacity requirements, and estimate projected shipping cask fleets. The programs are tailored to utilize information on the types of wastes being received, location of repositories and waste-generating facilities, shipping distances, time required for a given shipment, availability of equipment, above-ground storage capabilities and locations, projected waste throughput rates, etc.

Two basic models have been developed. The Low-Level Waste Model evaluates the optimal transportation policy for shipping waste directly from the source to a final destination without any intermediate stops. The Spent Fuel Logistics Model evaluates the optimal transportation policy for shipping unprocessed spent fuel from nuclear power plants (1) indirectly, that is, to an Away-From-Reactor (AFR) storage facility, with subsequent transshipment to a repository, or (2) directly to a repository.

## SNAPPS

(Written in 1978 by R. Classen)

Following abstract from an informal review by W. Waddell.

The SNAPPS code projects the supply of energy produced by the nation's reactors in the time period 1979-1983, by solving the following equation.

$$E = \sum_{i=1}^N \int_{1977}^{1983} P_i(t) dt$$

where

$P_i(t)$  = Power of Reactor  $i$ , and

$N$  = Number of Reactors in the U.S.

An uncertainty of the energy supply is also calculated. This uncertainty is due to the variance in the capacity factors, refueling times, and reactor construction time periods of existing reactors.

WASPR

ORNL/CF-78/32 (1978)

WASPR — A Waste Projection Code Incorporating  
Isotopic Decay

C. W. Kee  
(Oak Ridge National Laboratory)

A program has been written to calculate the volume, radioactivity, thermal power, isotopic composition, and toxicity of various waste streams resulting from projects of power levels of several reactor types in a nuclear economy. The program uses mass-flow projections, a description of waste characteristics, and reactor discharge compositions to produce tabular and isotopic output in a form described by the user. ORIGEN routines are used to calculate the effect of decays during and after the accumulation.