Mathematical Modelling of Regional Fuel Cycle Centres

by Leonard L. Bennett and Larry D. Reynolds

The concept of Regional Fuel Cycle Centres (RFCC) has attracted wide interest as a possible approach towards meeting the nuclear fuel cycle needs of many countries. As part of its study of the RFCC concept, the International Atomic Energy Agency is developing mathematical models and associated computer codes to analyse the economics and logistics of various strategies for management of spent nuclear fuel and waste materials.

The RFCC Study Project covers the transport, storage, processing and recycling activities starting from the time the spent fuel leaves the reactor storage pools and through all steps until the recycled fuel is in finished fuel elements ready for shipment to the reactor. All those activities considered as potentially being within the RFCC are shown in Figure 1 within the large grey-coloured rectangle. Production of fresh uranium supplies, uranium enrichment and UO_2 fuel fabrication are not included. Two groups of reactors are considered, one using fresh UO_2 fuel and the other using mixed oxide fuel (with or without some fresh UO_2 fuel). These reactors are presumed to be located in countries designated as A, B, ..., N. Upon discharge from the reactors, the spent fuel is placed in storage pools at the reactors, shown as "SFS".

After appropriate initial "cooling", the spent fuel is transported from each reactor site to a collective storage facility at the RFCC. At this stage, the overall economics of storing spent fuel for an extended number of years would be considered as an alternative to immediate reprocessing and recycling.

The first step is to ascertain whether it is necessary to reprocess the spent fuel and under what economic conditions (price of uranium, cost of separative work and value of plutonium) it would be worthwhile. If reprocessing of spent fuel is economically viable, or is essential in order to conserve fuel resources, then it is necessary to determine the appropriate time for making the fuel cycle facilities available, and the optimum throughput capacity of those facilities.

Initially, a regional fuel cycle centre might involve only the immediately needed facilities, such as those for spent fuel storage, with later expansion to other operations such as reprocessing. The optimum schedule for expansion would vary depending on the types and capacities of reactors being built in the different countries and depending also on the economic value of reusable uranium and plutonium. In any event, spent fuel would need to be stored until the accumulated inventory and the spent fuel discharge rate are adequate to economically utilize the reprocessing capacity when it is built.

Fissile materials and radioactive wastes comprise the two important classes of materials produced as a result of reprocessing. The recovered fissile materials, uranium and plutonium, may be returned to the fuel cycle. The plutonium may be mixed with recovered uranium,

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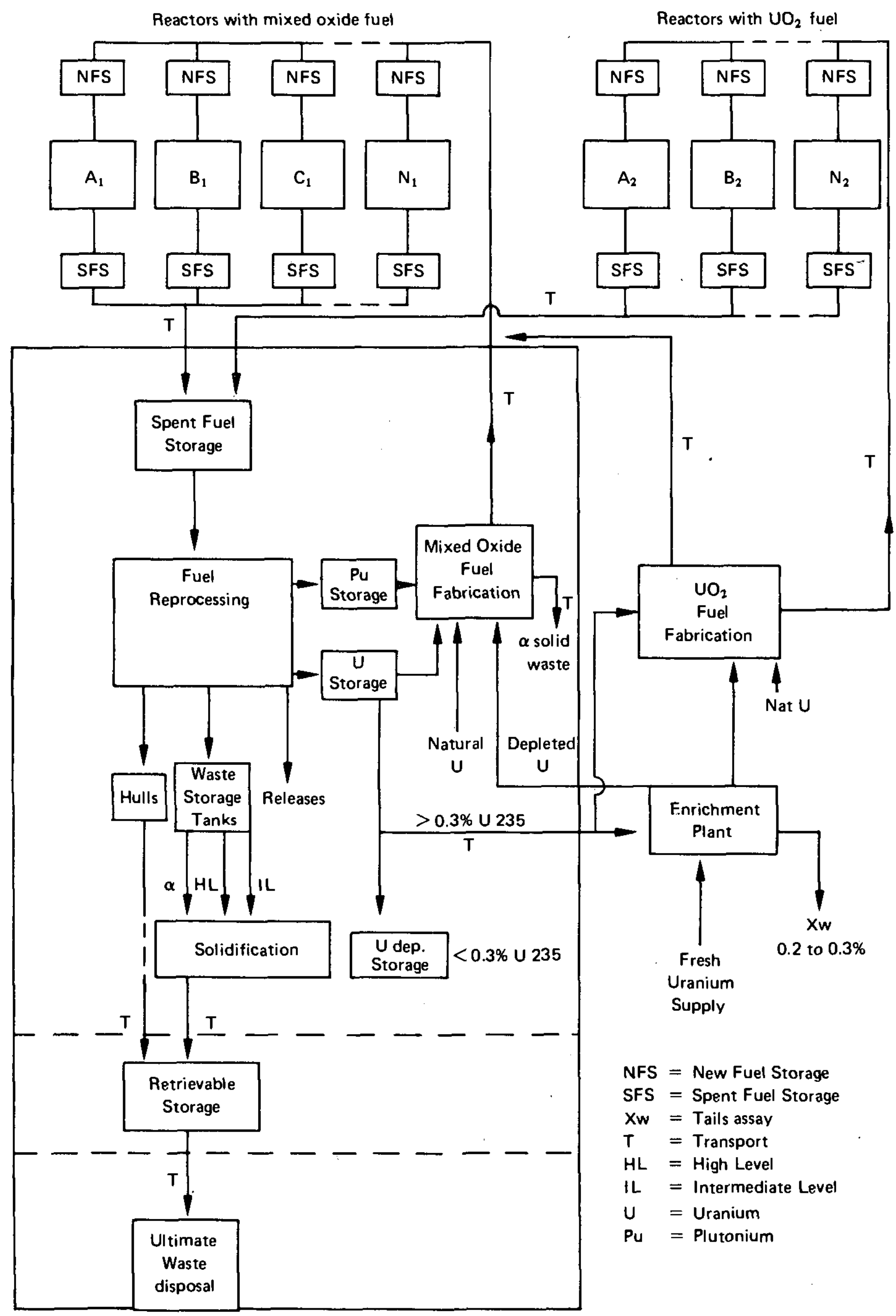
Figure 1. Concept of the Regional Nuclear Fuel Cycle Center



natural uranium or depleted uranium and fabricated into mixed oxide (MOX) fuel elements, and then transported to reactors which can utilize MOX fuel. The recovered uranium may go to a number of alternative points. Up to about 20% of the recovered uranium may be blended with plutonium. The remainder of the uranium may be stored or it may be recycled to heavy water reactors or enrichment plants, depending on its enrichment level and content of uranium-236 and other undesirable isotopes. In any event, reuse of the recovered uranium would reduce the requirement for fresh natural uranium, thereby producing an economic benefit.

The system for handling wastes consists of storage, treatment, transport and disposal. The facilities for retrievable storage and ultimate disposal of high-level wastes may or may not be on the RFCC site, depending on site conditions.

OBJECTIVES OF MATHEMATICAL MODELLING

One of the important criteria to be used in evaluating the merits of RFCC is the relative cost of spent fuel management using integrated regional facilities as compared with costs of using dispersed national facilities, taking into account the possibility and costs of long-term storage of spent fuel without reprocessing. The time distribution of capital investments and the material logistic requirements for a regional fuel cycle centre are important in the overall evaluation.

The primary objective of the mathematical modelling effort is to provide a methodology for analysing possible strategies for spent fuel management, with emphasis on economic analysis. This objective is being met by development of computer programs which describe the material flows, facility construction schedules, capital investment schedules and operating costs for the facilities used to treat the spent fuel. These computer programs are based on a number of technical studies that are developing the requisite operational and economic inputs.

NATURE OF THE COMPUTER PROGRAMS

The computer programs use a combination of simulation and optimization procedures for the economic analyses. Many of the fuel cycle steps (such as spent fuel discharges, storage at the reactor and transport to the RFCC) are described in physical and economic terms through simulation modelling, while others (such as reprocessing plant size and construction schedules, reprocessing load allocations to available plants, storage facility construction schedules, etc.) are subjected to economic optimization procedures to determine the approximate lowest-cost plans from among the available feasible alternatives.

There are various economic considerations which may make it desirable to plan for a delayed introduction of reprocessing. These considerations include:

1. Economies of scale may provide incentive for a delay in reprocessing, in order to allow a larger plant to be supported by a backlog of stored fuel.

2. The cost of reprocessing and recycling of uranium and plutonium in thermal reactors may not be offset by the value of the recovered uranium and plutonium until uranium and enrichment costs have risen. An additional factor would be the value placed on plutonium to be used as fuel for fast breeder reactors.

The RFCC model is planned to be sufficiently detailed so that it can explore various tradeoffs in order to make a near-optimum selection of reprocessing plant sizes, introduction dates, and fuel throughputs. This includes flexibility to describe and treat costs for probable options of storage-versus-reprocessing, delayed-versus-immediate reprocessing, local-versus-regional facilities, etc.

Figure 2 shows a schematic of the different segments of the present RFCC fuel cycle model. Each block represents a sub-model that describes the specific processes and costs involved in that activity. Certain of these sub-models involve optimization procedures.

THE RFCC SIMULATION MODEL

This model simulates the flow of fuel and waste materials through the various transport, storage and processing facilities, and calculates the cost of constructing and operating those facilities.

The distinguishing characteristic of this model is that it has no computerized optimization or decision-making capability. The user must specify the commissioning date and throughput capacity of all the major facilities, such as reprocessing plants and MOX fuel fabrication plants. Given these plant schedules, spent fuel discharge rates and cost data, the simulation model will perform an economic analysis covering the construction and operation of the proposed facilities. This cost calculation includes spent fuel transportation and storage costs, waste management costs, and credits for the value of recovered uranium and plutonium. In addition, the computer program prints out a detailed report on the annual quantities of such materials at each stage of the fuel cycle.

The following sections present a description of the major segments of the computer model diagrammed in Figure 2.

Reactors Model. The FURY model is used to calculate the annual quantities of spent fuel being discharged from reactors in individual countries. Input data consists of:

(1) Nuclear power capacity growth projection for each country, by reactor type (e.g. PWR, BWR, HWR);

(2) Average plant capacity factor;

(3) Spent fuel characteristics, quantities per GWe-year of reactor operation.

The spent fuel characteristics to be treated were selected to allow convenient description of the spent fuel in economic terms. The characteristics selected are:

A. Uranium content, in terms of

   (1) Actual amount of uranium;

   (2) Natural uranium feed equivalence, based on uranium enrichment;

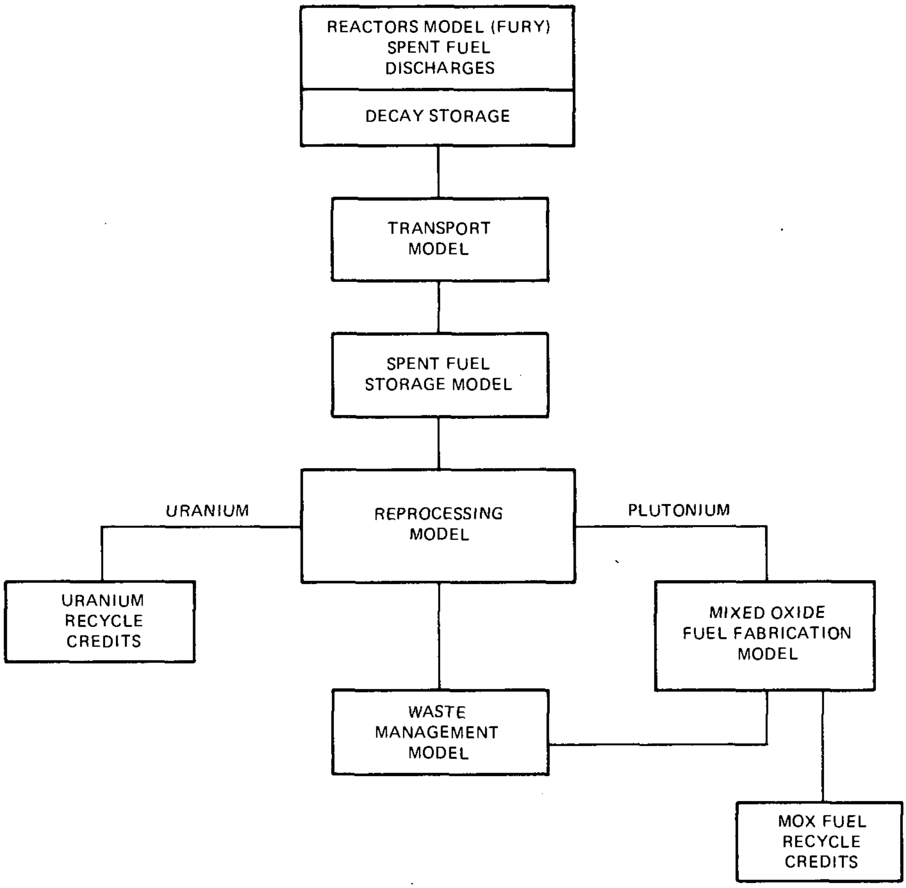
   (3) Separative work feed equivalence, based on uranium enrichment;

B. Plutonium content in terms of

   (1) Fissile plutonium;

   (2) Total plutonium.

Figure 2. Major Segments of Fuel Cycle Model for RFCC Study Project



These characteristics allow calculation of appropriate credits for recovered uranium and plutonium without the need to keep track of enrichment of individual batches of fuels. These characteristics can be averaged over any number of batches, whereas it is incorrect to simply average uranium enrichment (although the error is small if the enrichments are not greatly different).

Spent Fuel Transportation Model. After an appropriate decay storage time at the reactor site the model simulates the passage of the spent fuel through various handling and transportation operations, ending with its arrival at the RFCC storage facility. This simulation includes treatment of required capital investments, operating and shipping costs and time delays in shipment.

Spent Fuel Storage Model. The spent fuel is received at the RFCC and placed in normal buffer storage, mainly to provide inventory for uninterrupted operation of the reprocessing plant, and also to allow for efficient collection of spent fuel into reprocessing "campaigns".

Additional storage capacity will be required if the spent fuel is being received at a rate higher than the reprocessing capability. In this case, it is impossible to accumulate the excess fuel in the buffer storage, and additional interim storage must be provided. Interim storage would likely be needed while reprocessing plants are being built.

The computer model calculates the quantity of spent fuel received each year, and also the quantity that can be reprocessed in that year. The amount to be placed in interim storage is obtained by difference. The cumulative requirement for storage capacity is calculated by keeping account of the storage inputs and removals. Whenever the required storage capacity exceeds the available storage capacity, more storage facilities are added.

Reprocessing Plant Model. The present model of the reprocessing plant is extremely simple. The user can specify the schedule of reprocessing plant additions for each of up to three plant sizes. No more than one plant may enter service in any year. In addition, the user specifies for each plant the annual capital cost, the fixed annual operating cost, and the throughput-related variable operating cost ($/tonne spent fuel).

Spent fuel in interim storage from previous years is given priority in reprocessing. Thus, we are using a rule of "first in, first out" in allocating fuel to be reprocessed.

Mixed Oxide Fuel Fabrication Model. Data are being developed to provide capital and operating cost estimates for each major sub-facility in a mixed oxide fabrication facility. These costs will provide the basis for calculating the cost of MOX fuel fabrication as a function of fabrication plant size and throughput.

Uranium Credit. Recovered uranium is credited in relation to its value as enrichment plant feed material. Using standard enrichment formulae, the code calculates the recovered uranium "content" in terms of equivalent natural uranium and equivalent separative work. From input tables of natural uranium and separative work prices, the economic value of the recovered uranium is calculated.

Plutonium Credit. It is assumed that plutonium will be recycled to LWR as MOX fuels. Using an equilibrium cycle mass balance for a UO_2-fuelled LWR and for a MOX-fuelled LWR, the model calculates the net change in various characteristics due to plutonium recycle. An example of this calculation is shown in Table 1.

The coefficients calculated by this procedure are used to assign economic credits to the recovered plutonium. They are used also to adjust the spent fuel discharge characteristics to reflect the fact that future discharges are changed by current recycle of plutonium.

Waste Management Model. Waste management facility sizes and throughput rates are based primarily on reprocessing plant sizes and throughputs. Wastes and scrap from MOX fabrication also will influence the facility's size and throughput rates.

The following data will be used as input for each major operation in waste management and disposal.

For storage, treatment and disposal facilities:

(a) capital investment cost;
(b) investment schedule;
(c) fixed annual operating cost;
(d) throughput-dependent variable operating cost, $/tonne spent fuel reprocessed.

Table 1: Model for Adjusting Material Flows for Plutonium Recycle

STEADY-STATE CHARACTERISTICS	NON-RECYCLE CASE (UO_2 RELOAD)	RECYCLE CASE		NET CHANGE PRODUCED BY PU RECYCLE	NET CHANGE PER KG PUF RECYCLED
		UO_2 FRACTION	MOX FRACTION		
CHARGE					
TOTAL U, KG	27 350	18 500	8 409	-441	-1.63
% U-235	3.200	3.200	0.711		
EQUIV. NAT. U, KG	192 980	130 535	8 409	-54 036	-199.91
EQUIV. SWU	103 586	70 067	0.0	-33 519	-124.01
TOTAL PU, KG	0.0	0.0	441.0	441.0	1.632
FISSILE PU, KG	0.0	0.0	270.3	270.3	1.000
UO_2 FUEL FAB.	27 350	18 500	0.0	-8 850	-32.74
MOX FUEL FAB.	0.0	0.0	8 850	8 850	32.74
DISCHARGE					
TOTAL U, KG	26 167	17 679	8 190	-298	-1.10
% U-235	0.930	0.930	0.320		
EQUIV. NAT. U, KG	40 110	27 099	0.0	-13 011	-48.13
EQUIV. DEPL. U, KG	0.0	0.0	8 190	8 190	30.30
EQUIV. SWU	5 064	3 421	0.0	-1 643	-6.08
TOTAL PU, KG	254.9	172.4	273.1	190.6	0.705
FISSILE PU, KG	180.1	121.8	151.2	92.9	0.344

For transportation steps:

(a) cost of transporting the respective materials between facilities, \$/tonne spent fuel reprocessed.

DESCRIPTION OF RFCC OPTIMIZATION MODEL

This model attempts to determine the economic optimum schedule for expansion of reprocessing capacity, considering spent fuel discharge rates, economies of scale of larger size reprocessing plants and the added cost of interim storage facilities needed to accumulate an operating inventory for the larger plants. The planner provides various capital and operating cost data for the several possible sizes of reprocessing plants, as well as capital and operating cost data for interim storage facilities. The optimization model then determines the lowest cost strategy for spent fuel storage and reprocessing, including the cost credits for recovered uranium and plutonium.

The optimization method presently employed is "backward dynamic programming". This technique has the ability to select the optimum expansion schedule for a reprocessing plant over the planning time period by examining a finite number of feasible conditions, or "states", that can exist in each year of the time period. A "state" of the system is characterized by a discrete reprocessing capacity and a discrete amount of spent fuel in inventory storage. The dynamic programming procedure finds the schedule of reprocessing capacity and inventory storage levels which leads to the lowest cost.

CONCLUSION

The optimization and simulation models can be used advantageously in an iterative fashion to make a detailed analysis of spent fuel management strategies. The dynamic programming model can determine the approximately lowest-cost reprocessing schedule, but will not provide complete detail for all the cost items. This schedule can then be used as input for the simulation model, which will carry out a more detailed analysis of the spent fuel management steps. The simulation model can also be used to seek further cost optimization by examining details that cannot be incorporated into the dynamic programming. Thus, the combined capabilities of the two computer codes should enable a fuel cycle planner to analyse a wide range of strategies for spent fuel management.