TRANSPORTATION AND STORAGE OPTIMIZATION OF SPENT NUCLEAR FUEL IN THE UNITED STATES

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ABSTRACT

In 1987, the U.S. Congress amended the Nuclear Waste Policy Act, establishing an independent body known as the Monitored Retrievable Storage Review Commission. The mandate of the Commission was to review DOE's assessment of the advantages and disadvantages of the Monitored Retrievable Storage (MRS) facility and to evaluate the need for an MRS. The MRS Review Commission asked ICF Technology Incorporated to develop a systems integration and transportation analysis model that would aid their evaluation for Congress. The resulting model (Model for Analysis of System Risk And Cost - MARC) was adapted from an earlier model (TRICAM) written for the DOE. MARC was made available to the Commission to calculate the costs and risks (both radiological and non-radiological) of alternative spent fuel storage configurations within the Federal Waste Management System.

Two of the over 30 MARC scenarios run by the MRS Commission are used to demonstrate the use of MARC in evaluating alternatives in terms of system costs and risks. These two cases are initially run in a cost minimizing mode and then in a risk minimizing mode in order to compare the difference in the value of risk for each system configuration. This example demonstrates the kind of insights MARC can yield and its utility in policy-making.

INTRODUCTION

Storage of spent nuclear fuel which is accumulating in the United States from the commercial production of electrical power is presently dominating the debate over its ultimate fate. U.S. Department of Energy (DOE) Secretary James Watkins made it clear in his remarks to Congress in November 1989 that the Department is continuing in its responsibility to locate, investigate, and license a permanent geological repository. However, the realistic date for the opening of the first high level nuclear waste repository is recognized by the DOE to be some years into the 21st century. In the meantime storage of spent nuclear fuel at the point of origin will become increasingly difficult. To alleviate the shortage of storage capacity, several alternative storage means and locations have been proposed since the early 1970's.

In 1987, the U.S. Congress amended the Nuclear Waste Policy Act, establishing an independent body known as the Monitored Retrievable Storage Review Commission. The mandate of the Commission was to review DOE's assessment of the advantages and disadvantages of the Monitored Retrievable Storage (MRS) facility and to evaluate the need for an MRS.

The MRS Review Commission asked ICF Technology Incorporated to develop a systems integration and transportation analysis model that would aid their evaluation for Congress. The resulting model (Model for Analysis of System Risk And Cost - MARC) was adapted from an earlier model (TRICAM) written for the DOE (1). MARC was made available to the Commission to calculate the costs and risks (both radiological and non-radiological) of alternative spent fuel storage configurations within the Federal Waste Management System.

This paper describes the MARC model and presents an example of how MARC can be used in support of decision-making for the high-level waste management program. Specific data developed by the MRS Commission is used for this discussion. The estimated impacts of storing and transporting spent nuclear fuel from the 125 commercial nuclear power reactors to a federally-owned repository in Nevada are presented. Cost and risk impacts are discussed for a system both with and without an MRS, generically located in the United States.

MODEL OVERVIEW

MARC is a single-commodity, constrained-optimization network model of the nation's commercially-generated spent nuclear fuel. The parameters optimized in MARC are cost and radiological risk. The scope of MARC covers the entire waste management system including the generation and temporary storage of spent fuel at the reactors (in pools or in dry-storage), storage and processing at an MRS, transportation from the reactors and/or the MRS to the repository, and final packaging and burial of the spent nuclear fuel at the repository.

MARC offers several advantages over the analytical tools previously used in the OCRWM program. It employs the classical methodology used in Operations Research where alternatives are evaluated in terms of optimal conditions. The advantages of optimization over the more typically used simulation approach have been documented in earlier papers (2). MARC allows the analyst to see the impact of specific tradeoffs in storage and transportation strategies and to place these tradeoffs into a broader context. For example, a strategy that increases transportation impacts may look unattractive if transportation costs/doses are the only parameters considered. When the strategy is evaluated in the context of other system costs/risks (e.g., consolidation, storage at reactors and the MRS) it may in fact be superior. MARC ensures that alternatives are evaluated taking into account such intra-system tradeoffs.

MARC is designed to be extremely easy to use, with the objective of broadening the user-group as much as possible. Too many computer models have been built which no one but the developers can use. Practically any person with an interest in, and knowledge of, the OCRWM program, can use MARC. This has been achieved through a menu-driven module for generating scenarios (supported by over 80 help/information screens) and through easy-to-read output reports.

MARC enables the simultaneous and consistent evaluation of cost and risk. Thus, the decision-makers can select options on the basis of the preferred combination of these dual policy objectives. This capability is demonstrated in the example application presented later.

MODEL OPERATION

The network structure of MARC is described in some detail in "Nuclear Waste: Is There a Need for Federal Interim Storage?" (3). MARC's user-interface is implemented in a personal computer environment (PS/2 Model 50 or higher) and the optimizing module is implemented on a VAX mainframe. MARC was designed to minimize the level of computer-related experience required to generate, run, and analyze alternative scenarios.

To run MARC, the user generates a scenario via a menu-driven program, described below, on a personal computer. The scenario files are then uploaded to the mainframe where the optimizer is executed. The output is downloaded to the PC for printing (the output can also be printed from the mainframe). The detailed procedure for running MARC is documented in the MARC User Manual (4).

The user-interface is organized into eight menus and several nested sub-menus, which are summarized below. The interested reader is referred to the MARC User Manual for a more comprehensive discussion of this topic.

- **System Configuration.** By this menu, the user specifies the number of DOE facilities to be modeled. Up to three MRSs and two repositories can be modeled simultaneously. The user also selects the spent-fuel forecast to be used and the reactors to be included in the analysis.
- **Facility Operations.** This menu and its sub-menus are used to specify the operating schedule, throughput rates, the maximum inventory allowed and the modal split (of fuel receipts) at each of the DOE facilities.
- **Consolidation.** The user specifies whether fuel will be consolidated and if so, whether this is to occur at the MRS or the repository. Consolidation costs and doses are input through sub-menus. (Consolidation at the reactors can be modeled but this requires careful modification of the overall system, since MARC is essentially a single-commodity model.)
- **Packaging.** Through this menu, the user specifies the packaging to be modeled and where packaging is to occur. There are obvious connections with the way consolidation was modeled. For instance, if the MRS is to consolidate fuel, a consistent packaging function must also be defined.
- **Storage.** This menu and its sub-menus are used to define at-reactor and at-MRS dry storage cask technologies. Different technologies can be assigned to different reactors. This may be done to account for crane capacity limitations, rail-access constraints, etc.
- **Transportation.** A series of menus and sub-menus are used for defining the transportation system from reactors to each DOE facility and between such facilities. The user defines the cask technologies, and specifies the mode(s) -- rail, truck, or both -- and cask-type(s) to be used for shipments between each origin-destination pair. In addition, the user also selects the type of service, e.g., regular or dedicated rail, for each origin-destination pair. (Sophisticated screen editing features greatly simplify this otherwise cumbersome, repetitive exercise.)
- **Disposal.** The user specifies the costs and doses incurred at the repository in disposing of the waste.
- **Other Input Data.** In this menu, the user is asked for information on the minimum fuel age for shipment eligibility, whether reactors are to be allowed to have ending inventory, the optimization criteria, the base year and discount rate (if any), etc.

It should be observed that at the end of the scenario-generation exercise, the user will have modeled the entire waste management and disposal system -- from the spent fuel projections to the final disposal at the repository.

The archival system built into MARC allows the user to add a short description of the scenario which becomes a part of the scenario file. Once a scenario is saved, it can be used as a template for defining other scenarios. This capability is very useful in cases where only a few parameters are changed. The scenario specifications are saved in a formatted file which can be viewed on-screen or printed, making the tracking and retrieval of scenarios convenient and simple.

MODEL APPLICATION

Two of the over 30 MARC scenarios run by the MRS Commission are used to demonstrate the use of MARC in evaluating alternatives in terms of system costs and risks. This example demonstrates the kind of insights MARC can yield and its utility in policy-making. The particular data used in this example were developed by the MRS Commission staff and are adequate for the purposes of this demonstration.

Scenario 1 refers to a system without an MRS in the system (No-MRS). Scenario 2 includes an MRS, generically located in the eastern half of the United States (MRS). The salient assumptions underlying these scenarios are summarized in Fig. 1.

MARC was first run in a cost minimizing mode for both scenarios. Table I is a summary of the resulting costs and risks under the two scenarios. Each value shown in Table I is supported by other tables in MARC which provide detailed breakouts by sub-categories, facility type, and year; if desired, further details can be generated on an annual, reactor-by-reactor basis in the model.

From Table I, it can be seen that the No-MRS system is less costly than the MRS system by $770 million. In terms of cost alone, the No-MRS option appears superior. However, when the relative risks are taken into account, a different conclusion may be reached depending on the value placed on risk. Every MARC analysis includes the risks associated with the scenario being analyzed. In the present case, it can be seen from Table I that the system risk for a No-MRS system is higher by 13,700 person-rem. Thus, moving from a No-MRS to a MRS system involves trading off cost in favor of risk at the rate of $56,000 per person-rem. If the societal valuation of risk is higher than $56,000 per person-rem, then the MRS option becomes superior.

Note that this conclusion is made in the context of operating the two systems so as to minimize cost. The conclusion might change if the systems were operated to minimize risk because the opportunity for reducing risk differs between the systems. To examine this, the scenarios

TABLE I
Cost/Risk Results (Cost-Minimization)

Description	No-MRS Cost (1989 $m)	No-MRS Risk (1000 prem)	MRS Cost (1989 $m)	MRS Risk (1000 prem)
SYSTEM TOTAL [a]	**3,895**	**34.1**	**4,665**	**20.4**
TOTAL VARIABLE	**2,153**		**1,139**	
At-Reactors:	1,605	13.5	280	1.8
Pool Inventory [b]	*689*	*0.0*	*86*	*0.0*
Dry Storage [c]	*915*	*13.5*	*194*	*1.8*
At-MRS [c]	n/a	n/a	249	0.6
At-Repository	296	8.4	296	8.4
Transportation	253	12.2	315	9.5
TOTAL FIXED	**1,743**		**3,526**	
At-MRS:	n/a		1,784	
At-Repository:	1,743		1,743	

[a] The reader is cautioned against attempting a direct comparison of the system costs presented here and other estimates generated by the DOE, because (1) these costs are discounted and so specific to the schedule modeled and (2) certain pre-operation 'development and evaluation' costs were not included by the Commission staff in MARC. As emphasized, the purpose of this paper is to demonstrate the use of MARC in comparing alternatives. The precise numbers are not as important in this context. They would be, of course, if the application were for establishing policy.

[b] Costs and doses incurred from pool maintenance in the years beyond the 'normal' decommissioning period (5 yrs. by assumption) that the removal of spent fuel from shut-down reactors is delayed.

[c] Includes the cost of the dry casks, loading, placement and unloading.

Description	No-MRS	MRS
Repository Schedule (Start/End years)	2013/2045	2013/2045
MRS Schedule (Start/End years)	n/a	2000/2045
Maximum Capacity at MRS	n/a	Unrestricted
Quantity of Spent Fuel (MTU)	86,756	86,756
Destination of shipments from Reactors	Repository	MRS <u>or</u> Repository
Transportation Mode	All reactors can ship by truck Reactors with adequate facilities can ship by rail	All reactors can ship by truck Reactors with adequate facilities can ship by rail
Transportation Service from Reactors	Individual casks by truck 3-cask one-way dedicated rail	Individual casks by truck 3-cask one-way dedicated rail
Transportation Service from MRS	n/a	5-cask round-trip dedicated rail
Transportation cask capacity (PWR/BWR)	Truck: 3/7 Rail: 21/48	Truck: 3/7 Rail: 21/48
Packaging	From-reactors: Bare assemblies At-repository: Intact in containers	From-reactors: Bare assemblies From-MRS: Intact in canisters At-repository: Intact in containers
Dry storage cask capacity (PWR/BWR)	At-reactors: 21/48	At-reactors: 21/48 At-MRS: 28/70
Minimum fuel-age for shipment eligibility	5 years	5 years
Discount rate for cost and base year	4% (1989)	4% (1989)

Fig. 1. Scenario Assumptions.

were run in a risk-minimization mode which involves changing a single variable -- optimization criteria. This is easily accomplished through MARC's user-interface, by using the previous scenarios as templates. All other parameters were left unchanged from their respective previous values, ensuring complete consistency with the previous (cost-minimization) scenarios. The cost/risk results are shown in Table II.

The data in Table II indicate that if the two systems were operated to minimize risk, the higher cost of the MRS system ($1,262 million) is accompanied by a risk reduction of 9,100 person-rem. Thus the cost/risk tradeoff here is much higher, at $139,000 per person-rem, than in the cost-minimization case. Unless the societal valuation of risk is higher than $139,000 per person-rem, the No-MRS system is preferred.

Having presented the pair-wise comparisons, the complete set of cases can be compared simultaneously in a cost/risk framework. Figure 2 is a plot of the four cases (labelled I through IV) in a cost-risk plane, with cost ($ billions) on the y-axis and risk (1,000's person-rem) on the

TABLE II
Cost/Risk Results (Risk-Minimization)

Description	No-MRS Cost (1989 $m)	No-MRS Risk (1000 prem)	MRS Cost (1989 $m)	MRS Risk (1000 prem)
SYSTEM TOTAL [a]	**4,532**	**27.5**	**5,794**	**18.4**
TOTAL VARIABLE	**2,789**		**2,268**	
At-Reactors:	2,250	7.0	1,552	0.6
Pool Inventory [b]	*1,357*	*0.0*	*1,351*	*0.0*
Dry Storage [c]	*893*	*7.0*	*200*	*0.6*
At-MRS [c]	n/a	n/a	161	0.3
At-Repository	296	8.4	296	8.4
Transportation	244	12.2	260	9.2
TOTAL FIXED	**1,743**		**3,526**	
At-MRS:	n/a		1,784	
At-Repository:	1,743		1,743	

[a] The reader is cautioned against attempting a direct comparison of the system costs presented here and other estimates generated by the DOE, because (1) these costs are discounted and so specific to the schedule modeled and (2) certain pre-operation 'development and evaluation' costs were not included by the Commission staff in MARC. As emphasized, the purpose of this paper is to demonstrate the use of MARC in comparing alternatives. The precise numbers are not as important in this context. They would be, of course, if the application were for establishing policy.

[b] Costs and doses incurred from pool maintenance in the years beyond the 'normal' decommissioning period (5 yrs. by assumption) that the removal of spent fuel from shut-down reactors is delayed.

[c] Includes the cost of the dry casks, loading, placement and unloading.

x-axis. Account must be taken of what is considered an acceptable cost-for-risk tradeoff (risk-premium) in order to determine the preferred solution. The risk-premium ($/person-rem) is simply the absolute value of the slope (ΔCost/ΔRisk) of any straight line drawn on this plane, such as AA. Obviously, risk-premium increases as the line AA is rotated clockwise. If the risk-premium is below $56,000 per person-rem (represented by line BB) then the No-MRS system would be selected and operated according to the cost-minimization solution (point III). If the risk-premium is higher than $56,000 per person-rem but less than $565,000 per person-rem (represented by line CC), then the MRS system would be selected and operated according to the cost-minimization solution represented by point IV. At higher levels of risk premia the (risk-minimization) MRS system (II) would be preferred. Note that in no case is it credible to argue for a risk-minimization No-MRS solution (I).

CONCLUSION

This paper demonstrates how MARC can be used to evaluate options for defining and operating the nation's spent nuclear fuel disposal system. At the center of the prevailing controversy surrounding the need for an MRS, is the issue of how much we are willing to pay to minimize the risks associated with storing and disposing of spent nuclear fuel. Through the application of MARC, the evaluation of the numerous alternatives can be conducted in a systematic, focused manner to facilitate consensus among the many interest groups involved.

Each MARC solution includes a complete set of logistics specifications which show the quantities of fuel to be

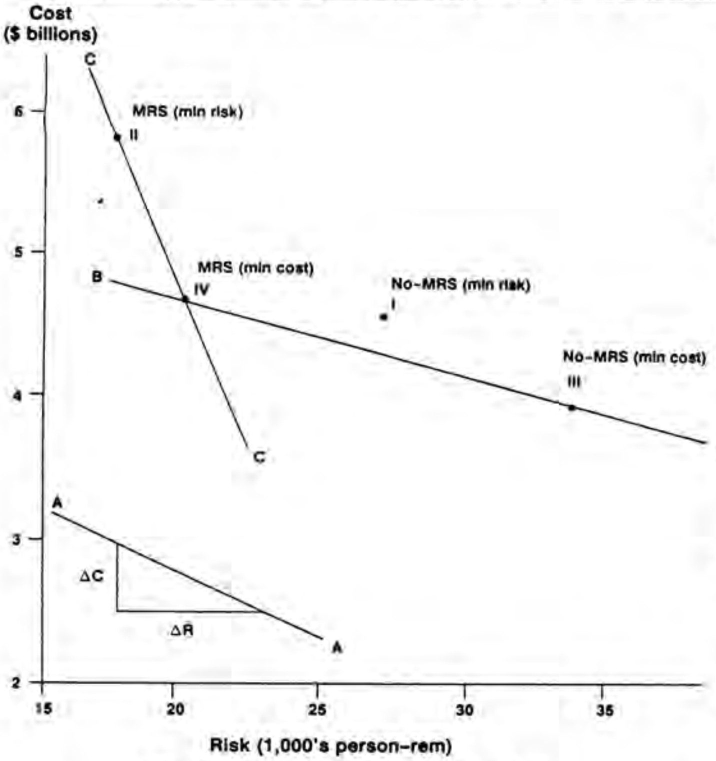

Fig. 2. Cost/Risk Trade-Off Analysis.

stored in dry storage in each year at every reactor, the quantity of fuel shipped to the MRS each year, and the quantity of fuel shipped to the repository each year. These data represent the most efficient way of managing spent fuel disposal for the selected system configuration. This aspect of MARC is not discussed in this paper due to space constraints. However, sample outputs are available in the MARC User Manual (4).

REFERENCES

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