NUCLEAR WASTE TRANSPORTATION: AN OPTIMIZATION MODEL

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ABSTRACT

The US Department of Energy, as part of its responsibility for the permanent disposal of commercially generated spent nuclear fuel and high-level radioactive waste, is charged with developing a transportation system that is safe and cost-effective. A network optimization model is being developed to assist the DOE in selecting among alternative system, equipment, and scheduling options to achieve this objective. This paper describes the formulation of the optimization model and presents one approach to its use in decision analysis.

INTRODUCTION

The US Department of Energy (DOE) is responsible for the permanent disposal of commercially generated spent nuclear fuel and high-level radioactive waste, referred to generally as waste in this paper, in a mined geological repository. The waste, generated at nuclear facilities spread across virtually the entire continental United States, will be shipped to the selected repository site. Three candidate repository sites are presently under consideration: the Hanford Site in Washington, the Yucca Mountain Site in Nevada, and the Deaf Smith Site in Texas. In addition, a monitored retrievable storage facility (MRS) is being considered for the consolidation and temporary storage of the spent fuel.

One of the DOE's objectives is to design a transportation system that is safe and cost-effective. An analytical tool is being developed to support DOE decision making in this regard, incorporating lifetime transportation risks and costs as the basic decision variables. It is a network optimization model that can be used to evaluate system, equipment and scheduling alternatives, subject to the applicable constraints, in terms of lowest achievable risk and cost.

The model will compute optimal solutions for these alternatives, given a set of assumptions and constraints. These solutions can then be compared and used as the basis for selecting between the alternatives. Such selections will be defensible because they will have been based on the lowest risks and costs achievable under each of the alternatives under consideration. It is important to recognize, however, that a solution yielded by the model is not a prescription for action. The model does not yield a single optimal solution; what the model does provide is the capability to compare and evaluate system, equipment and scheduling alternatives in a logical, fair and defensible manner.

This paper describes the formulation, design and a proposed application of this optimization model. The actual computer routine used in the model to perform the optimization is NETFLO which is documented elsewhere (1), and is therefore not discussed in this paper. The next section is an overview of the model, describing its overall structure and design. Each major component of the network is described in detail in the following section. Next, the objective function and its use in developing efficient solution frontiers for a given application are described.

It is hoped that this paper will stimulate interest in the application of constrained optimization techniques in other parts of the radioactive waste management program. The authors also hope that the paper will elicit comments and suggestions for enhancing the model, which is in the final stages of development.

MODEL OVERVIEW

The model network comprises the three types of facilities described above: the reactors at which the waste is generated and stored, the fuel consolidation and temporary storage facility (MRS), and the final disposal facility (repository). Each of the three facility types is modeled as a set of nodes. (For simplicity, the term "reactor" is used to signify both spent fuel and high-level waste generating facilities.)

The facilities are connected by arcs which represent the transportation alternatives available between them. For instance, two facilities between which both truck and rail service are available would be connected by two arcs, one for each mode. If there are two viable truck routes between a pair of nodes, each could be represented by an arc. Waste can be shipped from a reactor to the MRS or to the repository or, in specified cases, to another reactor.

The activity along these arcs is the quantity of waste shipped between two facilities in a given year. The risks and costs of shipping a unit of waste along an arc form the coefficients of the objective function in the model.

The facilities described above consist of sub-networks that model the alternative material storage capabilities available at these facilities. The nodes within these sub-networks are the temporary alternatives to transportation available at the respective facilities. If a reactor pool is filled to capacity, for instance, the fuel may be stored in dry storage casks at the reactor site, instead of being shipped to another facility immediately. This is only a temporary alternative, however, as all fuel must eventually be shipped out to the disposal facility.

The nodes within a facility sub-network are also connected by arcs, representing the handling and transfer activities within the facility. The activity on these non-transportation arcs is the quantity of waste handled or held in storage. The per unit risks and costs associated with these activities also enter as coefficients in the objective function.

The set of nodes and arcs described above represents the spatial network. A similar network is generated for each year of the program. Inventory arcs at the respective facilities provide the year-to-year connection in the model. Thus, the optimization occurs across both time and space.

The constraints under which the optimization is performed include the capacity limits at the various facility nodes, such as the maximum annual receipt rate at the MRS or its maximum storage capacity, and the usual material balance constraints. Capacity constraints are user-specified, so that they can be readily changed to reflect the most current values used by DOE, or to examine the system-wide implications of *proposed* changes. If these constraints are not specified by the user, the model reverts to default values, derived from the most recent system descriptions available (see, for example, Ref. 2).

NETWORK FORMULATION

The formulations of the three types of facilities are shown in Figs. 1, 2 and 3 and are described individually below. The network formulation depicted in these figures is for one year. In applications, similar networks would be generated for each year included in the analysis, with the inventory arcs at the reactors, the MRS, and the repository providing the year-to-year linkage in the model.

Reactor Nodes

As shown in Fig. 1, the general formulation of reactors includes three current year nodes: the reactor pool node, the dry storage node, and the aggregate shipping node. In addition, there are two inventory nodes. The flows of waste along arcs connecting these nodes are described below.

Reactor Pool Node. Waste can enter the current year reactor pool node from four sources. Discharges from the reactor during the year enter the reactor pool on arc 1. The previous year's inventory is carried over to the current year reactor pool node along arc 2. Transhipments from other reactor pools during the year enter on arc 3. Waste removed from dry storage for shipment enters on arc 8. The inflows on arc 1 are data obtained from the discharge projections compiled at the Pacific Northwest Laboratory and updated each year (3).

Outflows from the current year reactor pool node can also occur on three arcs. Waste can be transferred to dry storage casks at the reactor site (arc 4), it can be removed from the pool for shipment (arc 5), or it can be kept in inventory, i.e., transferred to next year's reactor pool (arc 6). Arc 6 is an example of the year-to-year linkage in the model.

Dry Storage Node. Waste is either placed in dry storage from the current year reactor pool node (arc 4) or it is brought forward as inventory from the previous year dry storage node (arc 7). Outflows from the current year dry storage node include removals for shipment (arc 8) and transfers to the next year dry storage node (arc 9). Arc 9 is another year-to-year linkage in the model.

Aggregate Shipping Node. The aggregate shipping node serves to constrain the total quantity of waste shipped from a reactor in a given year to no more than the annual shipping capacity of that reactor. Inflows into the aggregate shipping node are the removals from the reactor pool (arc 5). Shipments from this node can go to the repository (arc 10), the MRS (arc 11), or another reactor pool (arc 3A).

All reactors can ship by truck, but not all can ship by rail or barge. Separate shipment arcs (not shown in the figure) are modeled for each modal option available at a reactor. For example, a reactor that can ship by truck and rail would be modeled with two shipment arcs each to the MRS and the repository. Additional arcs can be defined, as needed, to represent different equipment options.

MRS Nodes

Figure 2 is the general forumation of the MRS node. It comprises three current year nodes: the receiving node, the storage node, and the shipping node. In addition, there is one inventory node.

Shipments from the various reactors enter the MRS receiving node either on arc 1 or on arc 1A, depending on the shipment mode. The waste is consolidated and placed in storage (arc 2) along with the previous year inventory (arc 3). Waste in the current year storage node is either transferred to the shipping node for shipment to the repository (arc 4) or to the next year

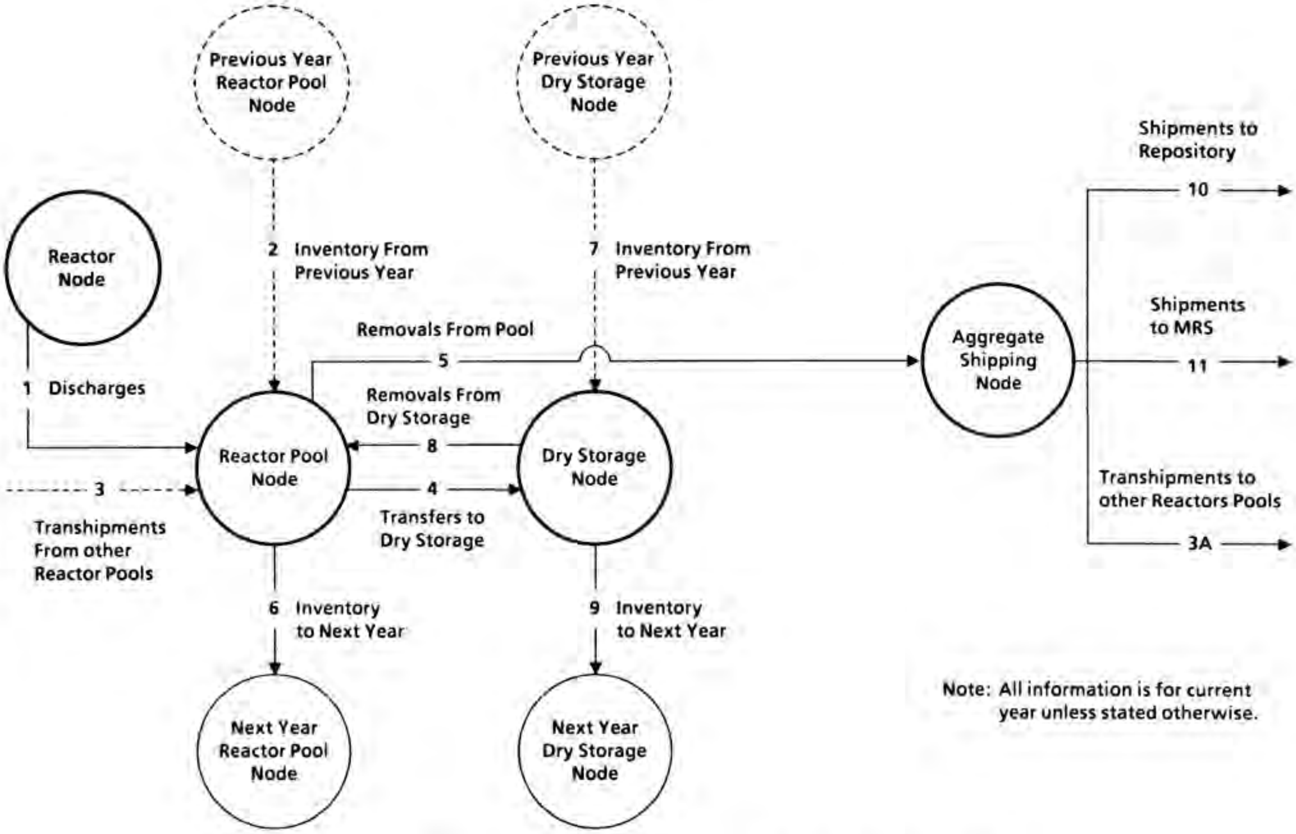

Fig. 1. General Formulation of the Reactor Node.

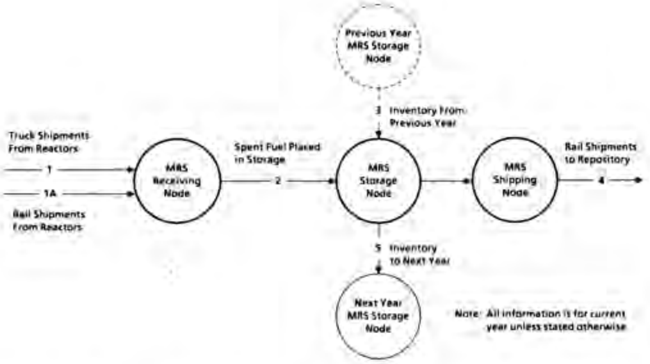

Fig. 2. General Formulation of the Monitored Retrievable Storage (MRS) Node.

storage node (arc 5). The MRS is assumed to ship to the repository by rail. However, if truck shipments are also to be considered, another shipment arc would be modeled.

Repository Node

The formulation of the repository is fairly straightforward, as depicted in Fig. 3. There is a receiving node for shipments received in the current year from the reactors (arcs 1 and 1A) and from the MRS (arc 2). This waste is added to the inventory from the previous year (arc 4) and carried forward to the next year inventory (arc 5). Note that there are no outflows from this node because the repository is the final disposal site for the waste.

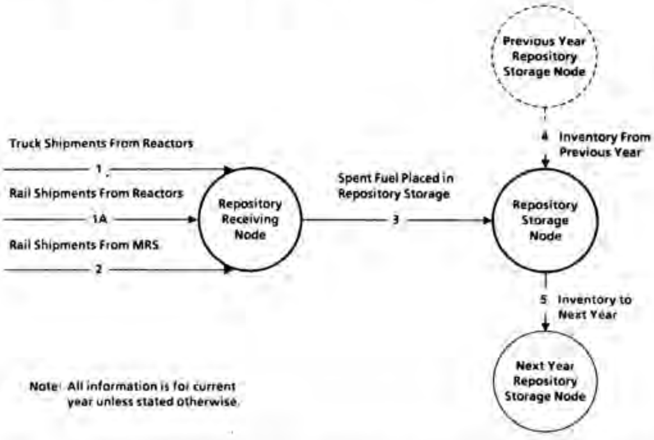

Fig. 3. The General Formulation of the Repository Node.

OBJECTIVE FUNCTION

The objective function of the model minimizes the total lifetime risks and costs associated with the flows described in the previous section, without violating any of the constraints. To include both risks and costs in the objective function, a composite variable is computed for every arc in the model. This variable, referred to as the objective function coefficient (z), is a weighted average of the per unit costs and risks associated with waste flows on these arcs. The weights are the relative values assigned to risk and cost, and are user-specified for each run. Specifically:

$$z_{ijt} = \alpha \cdot r_{ijt} + \beta \cdot c_{ijt} \qquad (1)$$

where

z_{ijt} = the objective function coefficient associated with moving one MTU (metric ton of uranium) of waste along arc ij (i.e., from node i to node j) in year t,

r_{ijt} = the risk associated with moving one MTU of waste along arc ij in year t,

c_{ijt} = the cost associated with moving one MTU of waste along arc ij in year t,

α = the relative weight assigned to risk, and

β = the relative weight assigned to cost.

The objective function in the model is defined as:

$$\text{Minimize:} \quad Z = \sum_i \sum_j \sum_t (z_{ijt} \times x_{ijt}) \qquad (2)$$

where

z = the value of the objective function, and

x_{ijt} = the quantity of material flowing along arc ij in year t, measured in metric tons of uranium (MTU).

TOTAL RISK AND COST

For any specified constraint set, the model computes values for the material flows (x_{ijt}) which, taken together across all arcs and all years, minimize the value of the objective function (Eq. 2). Note that the optimization occurs across the entire set of nodes and arcs over the life of the transportation program. This is not to say, however, that there will be activity on every arc in every solution; some x_{ijt}'s will most likely be zero.

The total risks and costs associated with the solution for any specified problem can be calculated from the solution results as follows:

$$R = \sum_i \sum_j \sum_t (r_{ijt} \times X_{ijt}) \qquad (3)$$

$$C = \sum_i \sum_j \sum_t (c_{ijt} \times X_{ijt}) \qquad (4)$$

where

R = the total risks associated with a particular solution, for all arcs and all years,

C = the total costs associated with a particular solution, for all arcs and all years, and

X_{ijt} = the computed values of x_{ijt} associated with a particular solution.

RISK-COST TRADEOFF

It was noted in the introduction that the DOE is responsible for developing a transportation system that is safe and cost-effective. It is clear that to accomplish this mission, both risk and cost need to be factored into the decision making process and the model has been designed with this specific purpose in mind. The model allows the analyst to generate a range of optimal solutions for a policy option by using different weights for risk and cost. By running the model with $\alpha = 1$, $\beta = 0$ in Eq. 1, the minimum risk solution is computed. At the other extreme, the minimum cost solution can be obtained by setting $\alpha = 0$, $\beta = 1$. Intermediate solutions can be computed by using other values for α and β.

For each solution, the total risks and costs can be calculated using Eqs. 3 and 4. These values can be plotted on a risk-cost plane, as shown in Fig. 4. In this figure, point A is the minimum risk solution, D is the minimum cost solution, and points B and C are examples of optimal solutions for different α and β values. The solution points shown in Fig. 4 represent the tradeoff opportunities between risk and cost that are possible under the policy being examined.

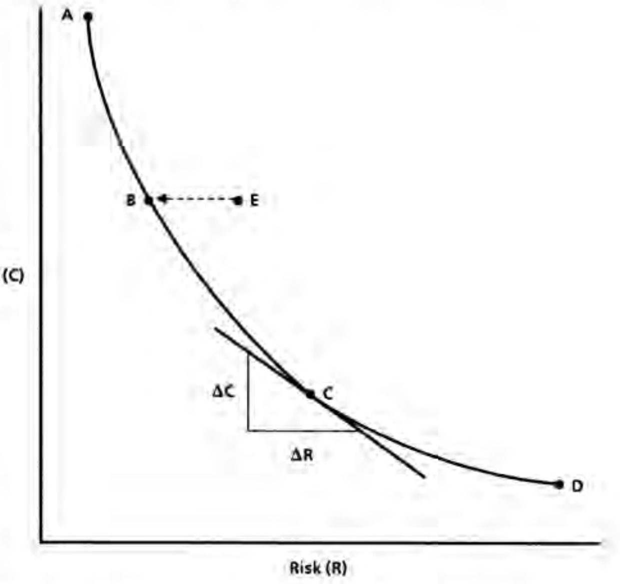

Fig. 4. Efficient Risk-Cost Tradeoff Frontiers.

The locus of all such points can be interpreted as a risk-cost tradeoff frontier. Moreover, because each point corresponds to an optimal solution for a particular risk-cost weighting, the tradeoff frontier is efficient. The slope of the efficient frontier at any point is $\Delta C/\Delta R$ (shown in the figure for point C), which can be interpreted as the "price" of risk.

The area under the efficient frontier is infeasible for the set of constraints under which the optimization occurs. The region above the efficient frontier is not optimal. While the optimization model solutions will always fall on the efficient frontier, other analytical tools may yield solutions in this region. Such solutions can be quickly shown to be sub-optimal. The solution point E shown in Fig. 4 is assumed to have been obtained through some other analytical approach. This point is not optimal because risk can be lowered without incurring any additional cost by moving to point B on the efficient frontier.

DECISION ANALYSIS

The model results can be used in a variety of ways to address different questions. One approach is described in this paper. Note, however, that although the model results serve as useful inputs, decisions cannot be based solely on them. There are other factors germane to a decision, such as budgetary constraints and uncertainties regarding the data and the future, all of which cannot be included in models such as the network optimization model presented in this paper. The decision makers will, however, need to incorporate such "external" considerations into the decision making process.

The following discussion is conducted assuming a "ceteris paribus" condition, i.e., all other things are equal. This enables discussion of the use of model results in decision making, assuming that all external influences are neutral.

The decision maker's attitude towards risk can be neatly represented in the "price" of risk which, as noted earlier, is simply the slope of the efficient risk-cost tradeoff frontier, i.e., $\Delta C/\Delta R$ (see Fig. 4).

Figure 5 shows a hypothetical efficient frontier. If the decision makers are highly risk averse, a solution point such as A might be selected. If the acceptable risk-cost tradeoff is lower, a point such as B, where the slope of the curve is lower than at A, may be selected. The key point here is that the decision depends, ceteris paribus, on the decision maker's attitude towards risk.

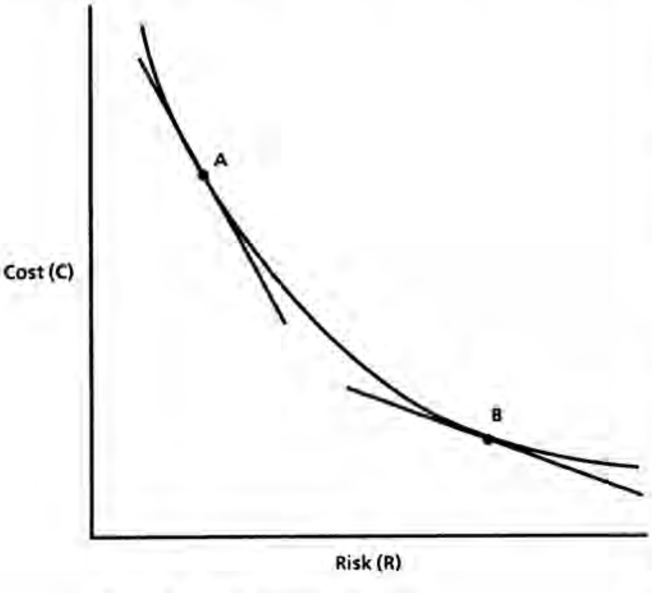

Fig. 5. Evaluation Policy.

To illustrate how this model can be used to compare alternative policies, consider a simple case where the decision maker is faced with a choice between two options. Figure 6 shows the risk-cost tradeoff frontier generated for each option by running the model with different values of α and β, as described above. The figure is drawn such that the slopes of the two curves are equal at A and B, and at C and D. If a high value is placed on risk, represented in the figure by points A and B, Option I would be selected. If the risk-cost tradeoff is lower, say it is represented by the slope at C or D, Option II would be preferred.

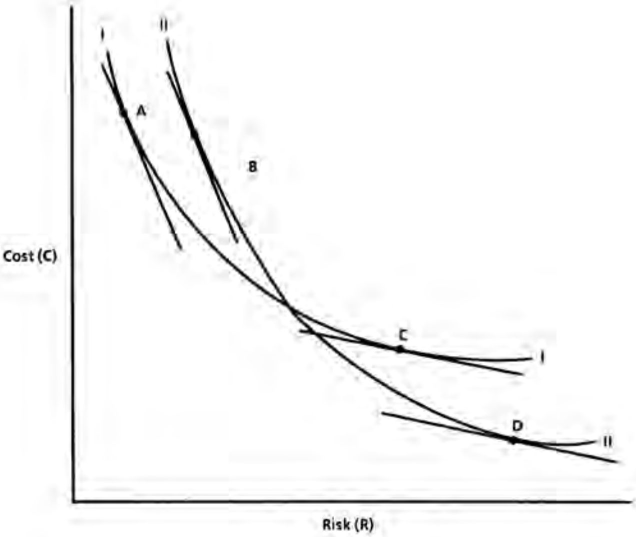

Fig. 6. Comparison of Policy Options.

CONCLUSION

This paper has described an approach for the use of optimization techniques in analyzing policy options. The presentation has been at a general level because, as noted in the introduction, the model is still under development. Once the development is completed and the necessary risk and cost data obtained, it is hoped that this approach will be used extensively in examining and resolving the wide spectrum of issues facing the DOE's waste transportation program. Above all, the optimization approach ensures that when two options are compared, the comparison is based on the optimal solutions attainable under each option. Without optimization, it is possible that the very specification of the scenarios under which options are compared could bias the results against one option in favor of another.

Finally, there are probably many other decision arenas in the waste disposal program where optimization techniques could be applied to advantage. The authors welcome discussions to explore such opportunities, to share the experience gained in the present effort, and to participate in identifying and formulating applications in other program elements.

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