ALLOCATION OF SPENT NUCLEAR FUEL TRANSPORT CASKS

by

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I. INTRODUCTION

The selection of the form of spent nuclear fuel disposition, currently under debate, will precipitate an immediate requirement for spent-fuel transport regardless of the disposition alternative chosen. The resulting demand for spent-fuel transport casks makes the allocation and scheduling of these extremely costly containers a crucial issue to reactor operating utility companies. Decisions with respect to the mode of transport, cask utilization, and numbers of casks employed are required. In this study, a time-dependent constrained transportation model of the cask scheduling problem is formulated with the objective of constructing a methodology for determining the minimum number of spent-fuel transport casks required to meet a fixed transport schedule. An iterative search procedure is used to determine utilization schedules for the casks which result in a minimum present-worth cash flow. To determine mode of transport, an economic comparison of transport alternatives is performed.

In light of the controversies and uncertainties surrounding the availability of adequate energy supplies, the present and projected energy situation in the United States can scarcely be considered secure. Recent examinations of potential energy supply alternatives indicate that nuclear power must play a significant role in the production of energy for the United States. The success of the nuclear power industry in meeting these needs is to be determined in part by the progress attained in understanding, completing, and operating the nuclear fuel cycle. Thus, the nuclear fuel cycle, the closing of that cycle, and the alternatives to that closure are of clear and immediate concern to assuring an adequate supply of energy for the nation in both the near and long term.

The controversy over the advisability of using nuclear power to generate energy in an energy deficient environment revolves around the management of radioactive spent fuel discharged from nuclear reactors. This controversy has led to the current interim moratorium on spent nuclear fuel reprocessing, with the resulting temporary storage of all offloaded spent-fuel. One consequence of the mandatory storage of spent-fuel is that the storage capacities of spent-fuel basins at reactor sites are severely pressed. Some form of relief for these basins must soon be provided and may call for spent-fuel transportation. More importantly, regardless of the nature of the eventual resolution of the controversy over spent-fuel management, transportation of the spent-fuel is necessary. The spent-fuel is to be transported from the reactor sites either to some type of reprocessing plant or to a permanent repository. The volume of spent-fuel traffic is potentially significant.

Public concern regarding the exposure of personnel and of the environment to radiation has lead to strictly governed packaging requirements where transportation involves radioactive materials.

To comply with existing regulations regarding spent-fuel maintenance, shielding, and packing integrity, expensive transportation casks are employed when transporting irradiated fuel assemblies. The actual type of cask used depends upon the mode of transport which is most significantly reflected in the cask weight. Given the expense of the transport casks and the necessity to transport spent-fuel, decisions required include the construction of a transport schedule, the choice of transport mode, the planning of shipment schedules to maximize cask utilization, and the determination of the number of casks employed.

This study does not address the problem of transport schedule construction. However, given such a schedule, the study does develop a methodology for determining the minimum number of required spent-fuel casks to meet the fixed schedule and for optimizing the cash flows associated with the use of the required casks. An economic comparison of transport alternatives must also be performed to determine which alternative is most attractive. Consideration of spent-fuel modes of transport is limited to the alternatives of truck and rail.

Then, the purpose of this study is threefold: (1) to determine the minimum number of casks required to meet a given pickup schedule for each mode of transport, (2) to determine an optimal cask utilization plan for this minimum number of casks, and (3) to compare the alternatives of truck and rail transport in order to determine which is economically most attractive. In pursuing these objectives, the study is organized as follows: Background information and a detailed discussion of the problem of spent-fuel allocation are provided in Chapter II. Chapter III contains a literature search summarizing pertinent research and results dealing with both transportation problems in general and with transportation problems within the nuclear fuel cycle. A mathematical model which includes consideration of the facts that each spent-fuel cask will be empty when returning from its destination and that the given transport schedule must be met is used to determine the minimum number of required casks. This linear mathematical model is formulated in Chapter IV. Chapter IV also contains the outline of an iterative search procedure which determines schedules minimizing the idle-time of each required cask. In Chapter V, a hypothetical case inferred from planned reactor operating schedules is formulated. The mathematical model of the base case is then solved for both the truck and the rail case. After determining the optimal number of casks for each mode of transport, optimal cask utilization plans for the indicated minimums are obtained. These schedules are determined by using the iterative search procedure outlined in Chapter IV. After obtaining both the minimum number of required casks and an optimal schedule for those casks for each mode of transport, an economic comparison of the two pure transport strategies is conducted. The results of this study are presented in Chapter VI. Chapter VII contains the conclusions drawn from these results and recommendations for future study.

For the reference case analyzed, 55 rail casks or 384 truck casks are required to meet the given transport schedule. For each transport mode, tables are provided which summarize cask utilization statistics such as the number of new casks required each year in the planning horizon, the number of casks retired each year, the cumulative number of casks in service at the end of each year, and a cask utilization factor for each year. Using the cask utilization plans obtained, six transport alternatives are compared to determine which is economically most attractive. Figure 1.1 illustrates the transport alternatives evaluated and the transport decisions which form their basis. For the 23 year planning horizon employed, results indicate rail transport is more economical than truck even when dedicated trains must be employed. Also, over a long planning horizon, cask purchase is preferable to cask lease.

One of the most important conclusions of the reference case analysis is that the allocation of spent-fuel casks can be modeled as a transportation problem with additional constraints. Based upon the scenario of spent-fuel cask demand projected, present transportation capabilities are exceedingly inadequate. Neglecting political uncertainties, the need to construct rail casks for the transport of spent-fuel assemblies is emphasized.

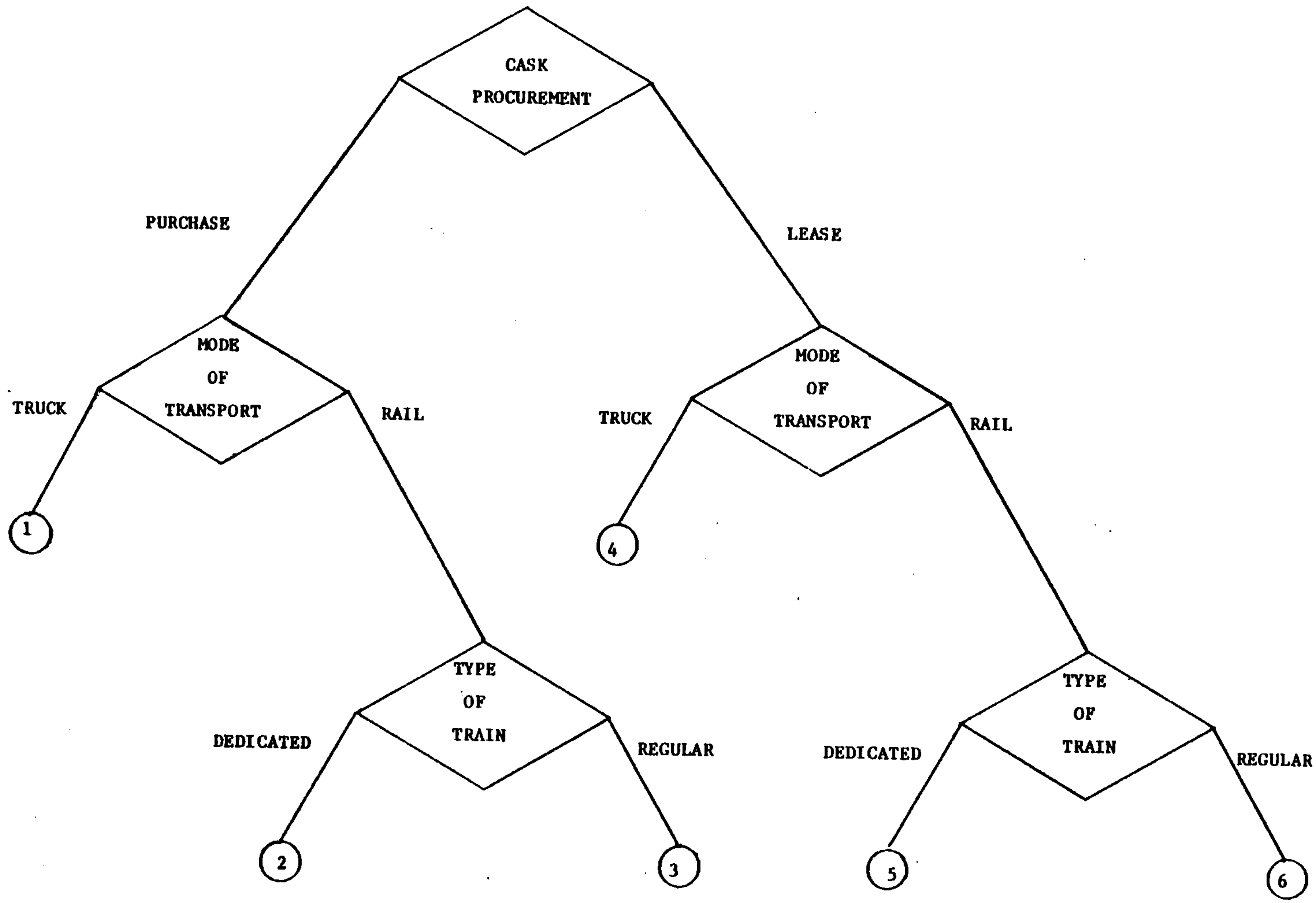


Figure 1.1

Spent-fuel transport alternatives.

II. BACKGROUND INFORMATION

Due to the increased production and use of nuclear fuel, the quantity of nuclear materials transported annually has steadily increased, especially in the last decade. Although comprising only a small portion of the hazardous materials currently transported in the United States, between 500,000 and one million packages containing radioactive materials are annually transported [1]. Of these shipments, approximately ninety-five percent are small packages of short-lived radioisotopes. However, the number of larger packages transported is expected to increase significantly with the expansion of the nuclear power industry. Public concern regarding the exposure of personnel and of the environment to radiation has lead to strictly governed packaging requirements where transportation involves radioactive materials. To comply with existing regulations regarding spent-fuel maintenance, shielding, and packaging integrity, expensive transportation casks are employed when transporting irradiated fuel assemblies. Determining the minimum number of required casks to meet a fixed pickup schedule, an optimal transportation schedule for these casks, and the most economically attractive model of spent-fuel transport then becomes an issue which must be resolved.

Within the nuclear fuel cycle, transportation of nuclear materials is required between operating facilities. In addition to the transport of unirradiated fuel assemblies, these operations include the movement of spent-fuel from reactors to reprocessing facilities or storage sites, the movement of highly radioactive waste products, and the movement of recovered plutonium [2]. The nuclear fuel cycle is the path followed by nuclear reactor fuel from the time it is mined as uranium ore to the time it is returned to the earth as a solid waste. First, the uranium ore is extracted and refined into uranium hexafluoride. Before this material can be used by the reactor, enrichment of the fissile isotope uranium-235 is required. This is accomplished with a mechanical separation process carried out at an enrichment plant. After enrichment, the gas is then transported to the fabrication plant where it is converted to uranium dioxide pellets. These pellets are loaded into fuel rods which are grouped into a fixed array. It is these arrays, fabricated fuel assemblies, which are inserted into the reactor core to generate electricity. Most reactors require approximately 200 such fuel assemblies to operate. Of these 200 assemblies, 1/4 to 1/3 must be replaced annually. After removal from the reactor, the fuel is highly radioactive, "hot," and is allowed to "cool." The fuel may be stored outside the core region for 10 days and in the reactor storage basin for another 120 to 180 days. This cooling period allows the activity to decay to a more tolerable level. At this point, reprocessing is feasible. Reprocessing of the irradiated fuel recovers uranium and plutonium which can be recycled and eventually used to recharge the reactor. The remaining radioactive wastes must be transported to permanent storage sites [2].

As previously mentioned, only four classifications of materials within the nuclear fuel cycle are considered with regard to nuclear transport legislation: unirradiated fuel, spent-fuel, recyclable materials, and wastes. This results from the inherent characteristics of the other materials involved in the cycle. For example, uranium hexafluoride meets the specifications of a low-specific-activity material [3]. Because of this classification, the hazards associated with its transport are considered to result from its chemical properties rather than from its radiological properties. Therefore, the transport of uranium hexafluoride, although subject to government regulation, is not discussed in greater detail. Only the transport of unirradiated fuel assemblies, spent-fuel assemblies, recyclable materials, and waste products are considered.

In the continental United States, most shipments of plutonium are made by truck. Federal statute prohibits air shipments until the integrity of the plutonium shipping containers can be insured under extreme accident conditions. Presently, plutonium can be shipped in either its liquid or its solid form. As of June 17, 1978, however, plutonium must be transported as a solid. Whenever large quantities of plutonium are transported, exclusive use vehicles must be employed. All shipments must conform to federal regulations for the transport of fissile radioactive materials. In addition, armed escorts accompany each shipment in a separate vehicle. Continuous radio communication with the vehicle is also maintained [4].

Unlike the cases of unirradiated fuel, spent-fuel, and plutonium, the transport of waste materials has no standard governing regulations for the entire category. Instead, separate provisions are made for the transport of each type of waste material. Because of the large spectrum of waste products within the nuclear fuel cycle, an analysis of the pertinent regulations for each type is beyond the scope of this effort. Thus, further discussion will be limited to the transportation of unirradiated fuel assemblies and of irradiated fuel assemblies.

Within the United States, truck, rail, aircraft, and barge transport are available to ship radioactive materials. For those materials within the nuclear fuel cycle, truck is the most commonly used carrier for unirradiated fuel while rail, truck, and barge transport are projected to be the primary sources of transport for spent-fuel [4]. In the case of irradiated fuel, the weight of the casks with adequate shielding prohibits the use of trucks unless an increased cooling period is used or fewer fuel assemblies are transported. Each mode of transport is subject to government regulations regarding the carriage of nuclear materials both in general and with respect to the specific cargo involved.

Regulatory standards require that the employed nuclear transport casks be capable of withstanding severe accident conditions regardless of the specific cargo. To insure this, the adequacy of the shielding and of the heat containment capability of the packages are tested after construction [1]. In addition to these initial tests, the casks must be rechecked prior to each use so that no regulations pertaining to temperature, pressure, or assembly are violated. Other functions are subject to periodic examinations after the cask assumes its transport schedule [4].

The Department of Transportation also regulates the acceptable external radiation level of the transport casks. A maximum of 200 millirems/hr on the cask surface and of 10 millirems/hr when three feet from the cask surface is allowed [3]. These regulations limit the radiation exposure of transport workers and of the general public and environment near the cask. Because of the additive effect of the radiation levels from an aggregation of packages, the number of casks which can be stored in one area or transported in one vehicle is limited. This limitation also insures nuclear-criticality safety when transporting or storing fissile radioactive materials [3].

More detailed legislation exists regarding specific nuclear cargoes. Unirradiated fuel assemblies, generally transported by truck, are packaged in cylindrical containers, each container housing two assemblies. The assemblies are first sealed in airtight plastic bags and then placed in metal containers which are transportable. In addition to providing containment and some shielding, this packaging protects the assemblies from the disturbances accompanying transport. Additional provisions require that no persons other than the driver and his assistants can be transported in the carrier and that no intermediate handling of the cargo will be permitted [3]. This prevents off-loading, storage other than at the fabrication plant or at the reactor site, and mid-route carrier transfer. The Department of Transportation has also imposed radiation dose-rate limits for transport workers and for the general public [3]. By using the described packages, these limits are met.

The transport of irradiated fuel is subject to more severe regulation due to increased radioactivity. Currently, standard designs for spent fuel transport casks are not imposed by government regulations. Instead, a maximum shell radiation level restriction is employed. The weight of the shielding required to meet this limit varies from 25 to 100 tons depending upon the number of fuel assemblies transported and upon the length of the employed cooling period [4]. This follows from the nature of the spent fuel. When removed from the reactor core, the irradiated fuel assemblies release large amounts of heat and radiation. The purpose of the cooling period is to provide a time for the reduction of these activities [2]. Consequently, the amount of shielding and therefore the weight of the transport cask is dependent upon the time allowed for cooling as well as upon the number of assemblies to be transported.

Because most states employ a 73,280 pound Gross Vehicle Weight limitation on highway vehicles, the transport of irradiated fuel is primarily by rail. The rail cask, weighing approximately 75 tons, carries 7 Pressurized Water Reactor spent-fuel assemblies [4].

This increased capacity results in fewer annual shipments than required with truck casks. However, certain limitations are involved with rail transport. First, not all light water reactor nuclear plants have rail service directly to the plant site. A recent report prepared for the United States Energy Research and Development Administration investigating current transportation capabilities indicates that 72.9% of reactor sites capable of handling spent-fuel casks have rail access [5]. For the remaining sites, either the rail cask must be trucked to the nearest railhead where it is transferred to a flat car or railroad construction must be considered. If transshipment is employed, the required materials handling and the potential radiation dose to transport workers is increased. Another disadvantage of transshipment is the excessive weight of the spent-fuel casks. The specific route and distance to be traveled by truck must be examined. The evaluation of potential road and bridge damage is used to determine whether overweight permits will be granted. The reactor facility must assume the cost of all damages while the assemblies are trucked. However, those facilities considering railroad construction face excessive costs to employ rail transport. Under ideal conditions, the estimated cost of constructing railroads is $31 per foot. This results in a cost of almost $164,000 per track mile [5]. Unless alternative modes of transport are more expensive, it is unlikely that railheads will be constructed at these sites. A second limitation is that the casks may be shipped by special trains at a maximum speed of 35 miles per hour. This increases both the cost and time required in spent-fuel transport. Finally, some railroads refuse to ship spent-fuel on their lines.

Legal Weight Trucks offer two major advantages over rail transport: (1) flexibility and (2) speed [5]. Also, those reactors without rail access can use truck casks. This eliminates the need for the facilities to transship spent-fuel or to construct railroads. With a capacity of only one Pressurized Water Reactor fuel assembly per truck, however, a large number of truck shipments are required to meet given pickup schedules. Two other limitations characterize truck transport. First, different states impose non-standard regulations which impede the transport of spent-fuel. Permissible transport hours and legal weight limits vary. Second, certain routes are restricted resulting in indirect travel paths.

Whereas barge transport is feasible with respect to weight limitations, the cost of erecting the required loading and unloading facilities is estimated to be in the $25,000-$1,000,000 range [3]. Unless other materials are also shipped by barge, this additional cost may be prohibitive. Another disadvantage occurs when reprocessing plants and disposal sites are not located adjacent to navigable waterways. Then, transshipment is necessary to transport casks from inland facilities to barge docks. The barge system of transport does possess two major safety advantages over railway systems. First, because of the low speed of transport involved, the severity of possible accidents is greatly reduced. Second, the potential dose-rate of radiation to the general public is reduced [3].

Regardless of the transport mode employed, the spent-fuel casks must meet certain handling requirements. Because the casks are loaded and unloaded under water, the cask is designed for such underwater operations. Decontamination may also be required. Upon arrival at a reprocessing plant, a cask is monitored to determine the exterior radiation level. If the cask is not contaminated, it is washed down outside the plant. Otherwise, it is washed inside the plant and the contaminated liquids are sent to a waste treatment plant. The next step in the decontamination process is to vent the cask and to remove the gases within. If the cask is designed for use with an internal coolant, the contaminated coolant is also pumped to the waste treatment plant. At this point, the cask is flushed and transferred to an unloading pool. Here the spent-fuel assemblies are transferred to canisters which are placed in storage racks. After rinsing with water, additional inspection and decontamination procedures may be used. Finally, the cask is re-mounted on the truck or upon the rail car employed and shipped from the site [6].

As indicated in the previous discussion, the radioactive material shipments within the nuclear fuel cycle are subject to the same transportation environment as nonradioactive cargo. Although some legislation regulates speed limitations and/or the use of escorts, the primary source of exposure protection lies in packaging requirements. These regulations attempt to ensure containment and to provide adequate shielding under both normal and accident conditions by specifying design provisions. Provision compliance results in an extremely high transport cost which in turn inflates the cost of generated electricity. The economics of nuclear power is then dependent in part upon transportation operations involving nuclear materials external to the reactor. Because of the cost of each transport cask, an optimal cask utilization plan is needed.

III. LITERATURE REVIEW

Within the nuclear literature, many publications [1, 2, 3] deal with the problem of transporting spent-fuel either to a permanent disposal site or to a reprocessing site. Rather than attempting to optimize the transportation system, these articles deal primarily with methods of improving packaging design and reducing radiation exposure risks. Methods of testing existing casks to insure adequacy is also an area of much publication [1, 4, 20].

In April, 1977, the Savannah River Operations Office of the U.S. Department of Energy published a discharged nuclear fuel storage and transportation analysis [7]. The publication addressed the problem of transportation requirements as a function of the number and types of shipping casks employed. Two underlying assumptions severely limited the model. First, rather than using specific reactor sites and storage or reprocessing locations to determine transport distances, a constant transport distance was used regardless of the origin or destination of a cask. Second, whenever a rail siding was available, rail casks were employed. Only when no rail siding was available were truck casks incorporated into the model. This assumption prevented an economic comparison of truck versus rail transportation. Another disadvantage of the model was the resulting noninteger solution. Fractional casks needed were determined resulting in the rule that any fraction must be rounded up.

Although no additional research has been done on the specific problem of transport in the nuclear fuel cycle as an optimization problem, relevant research is available in the area of similar transportation problems. These problems, depending upon the model formulation and the type of constraints used, can be solved using linear programming [11, 12, 15], dynamic programming [19], network theory [8, 9, 10], or heuristic techniques [18, 19].

Several models have been developed which adequately describe portions of the fuel transportation problem previously stated. J. L. Saha [8] formulated a linear programming model with the objective of minimizing the required number of buses to provide state transportation. His solution also identified a feasible transport schedule for the indicated number of buses. This solution was obtained by partitioning the required number of trips into groups. The groups are defined such that each could be operated by a single bus. The model was then solved as a maximum flow problem on a bipartite network. Unlike the model required for the transport of nuclear fuel assemblies, Saha's model built in provisions to allow for multiple stops between the specified starting place and time of a route and the terminal place and time of that route. In the case of the transport of spent-fuel, such stops, which form the basis of Saha's model, are prohibited by government regulations.

Much literature involving energy transport has centered upon the use of fuel tankers. Bellmore, Nemhauser, and Eklof [9] developed a decomposable algorithm which involves solving a sequence of shortest path problems to determine the solution of such a multi-period transportation problem. As is the case with nuclear reactors, a fuel requirement occurring in a specified period must be met by a shipment during that period or some previous period. Like Saha's, the model did permit intermediate offloading. This transshipment capability is provided in the model formulation: that of the traditional transportation problem but linked with inventory variables. Bellmore, Nemhauser, and Eklof [10] also addressed the problem of maximizing the number of possible deliveries when an insufficient number of tankers is available. Although this objective is infeasible for the nuclear problem, the solution technique is of interest. A longest chain algorithm was applied and used to find the maximum flow with a minimum cost on a directed linear graph.

Also working with oil tankers, Dantzig and Fulkerson [7] formulated a model with an objective of minimizing the number of tankers required to meet a fixed schedule and of determining schedules for these tankers. As in the case of the nuclear fuel cycle, the model was constrained to meet a fixed pickup schedule and delivery schedule. Although the original model is of the transportation form with additional constraints, the model is transformed into the classical transportation model and solved with the Simplex Procedure. Based upon this work, Gavish and Schweitzer [12] developed an algorithm which could combine trips in order to minimize costs.

This model differs from that of Dantzig and Fulkerson because different types of transport modes are allowable as well as different quantities of cargoes. The model does not require a pure strategy. In terms of the nuclear fuel problem, incorporation of this model would allow the employment of both truck casks and railway casks in the transport of the irradiated assemblies.

Transport workers have a maximum exposure dosage rate which cannot be exceeded. Such timing constraints have been incorporated in the model developed by J. J. McDonald [13]. McDonald employed vehicle scheduling techniques to plan the operation of collection services to be used in connection with medical services. The model solution determined the number and location of collection points, the number of collection vehicles required, and the schedule of the vehicles. Model constraints included a maximum transportation time to prevent specimen spoilage and the hours of duty of the vehicle drivers. Such constraints could also be used to specify the maximum period of exposure of a driver transporting casks.

An important aspect of the transportation models is the computational burden required for their solution. Those models which incorporate additional constraints become increasingly difficult to solve. Glover, Klingman, and Ross [14] have defined an algorithm which transforms linearly constrained transportation problems into standard form. The algorithm uses a constructive procedure to transform, if possible, a model into an equivalent bounded partial sum of variables with a single mode constraint. When such a transformation is not possible, the algorithm indicates there is no equivalent form. Klingman and Russel have investigated such models [15]. They developed a method of solution based upon the primal simplex method. The method requires that a spanning tree and a (q+1) x q matrix for each basis be stored where q is the number of additional linear constraints. The technique takes advantage of the triangularity of the spanning tree to reduce the required computations. Because the additional constraints used change the special structure of the transportation problem, all models incorporating such constraints are necessarily difficult to solve.

Another problem encountered when employing transportation models is the large amount of computer storage space required. Addressing this problem, Wagener and Benzin [16] have developed a new algorithm for computers with magnetic tape storage. This procedure, using little storage, requires on the average 1.5 iterations per source. The time per iteration is a function of the number of sinks employed in the model. The solution technique guarantees a unique optimal solution where no degeneracy occurs. An alternative approach was developed by L. Appelgren [17]. Here an algorithm for assigning cargoes to ships is presented based upon the use of a column generation technique. This technique does not guarantee an integer solution.

When an optimal solution is not required, heuristic techniques can be used which reduce the number of computations required. Lockett and Portlack [18] developed one such algorithm which assigns vehicles at the destinations and then works out a route back to the initial points. The indicated solution obtained produced a ten percent saving over conventional planning techniques. Traditional port cluster problems can also be solved using heuristic procedures of dynamic programming according to Brisken [19]. Such heuristic procedures are not appropriate when modeling the transport of spent-fuel since the potential savings are large because of the great expense of each cask.

Although these models deal with transportation problems, none are tailored to the allocation problem addressed in this study. For this reason, three distinct solution approaches are employed to meet the three objectives outlined. The employed solution procedure composed of these approaches is developed in Chapter IV.

IV. SOLUTION APPROACH

A. Introduction

Approximately 36 metric tons of spent-fuel are discharged per nuclear reactor annually [6]. Because present government regulations do not permit reprocessing, a substantial buildup in the quantity of irradiated fuel at the temporary storage basins has occurred. This spent-fuel must eventually be transported either to a reprocessing plant or to some disposal site.

As much as fifty percent of the fissile material originally loaded into the reactor core may remain in the off-loaded fuel assemblies [21]. However, the fission products present result in the need for extensive shielding to ensure containment. The cost of such shielding results in the use of expensive transport casks. Whether the transport mode selected for the shipment of the irradiated fuel is truck or railway, an optimal cask utilization plan is needed to minimize potentially substantial transportation costs and the costs of an excessive number of expensive casks.

For modeling the allocation of transport casks, the Dantzig-Fulkerson model [11] is particularly well suited. Three aspects of the model contribute to this suitability. First, the model is constrained by a fixed delivery schedule as must be the case in the spent-fuel model. Second, provisions of the Dantzig-Fulkerson model allow for the incorporation of the constraint that each transport cask must return from its destination empty. This is necessary since only after the cask returns to a reactor site is it reloaded for transport. Third, transshipment is not permissible in the Dantzig-Fulkerson model. Two other advantages make the model appropriate. It can be modified to incorporate the use of multiple shipments. This is very important when considering transport via truck because only a limited number of assemblies can be transported per truck cask. Multiple shipments are required to transport a sufficient number of assemblies to provide storage for offloaded assemblies. Another advantage is the ready availability of the input data. The model is based upon the fixed delivery schedule which must be met. Using a finite planning horizon, this schedule can be constructed by examining refueling schedules and storage capacity. For example, the capacity of a spent-fuel basin at a light water reactor site was originally designed to be 1.4 full core reloads [20]. One full core reload must remain empty because of safety considerations. By examining reactor reload schedules, transportation times can be computed for each reactor site.

The solution of the Dantzig-Fulkerson model indicates the minimum number of required transport casks. It also provides sufficient information for the determination of a feasible cask utilization plan. Using this feasible plan as an initial solution, an iterative search procedure designed to minimize cask idle time can be employed to optimize the cask schedules. Then, a utilization plan minimizing the present value of cask costs for the minimum number of transport casks is obtained.

For modeling the utilization of spent-fuel transport casks, the Dantzig-Fulkerson model is employed. This model is developed in Sections B, C, D, and E of Chapter IV. Section F of Chapter IV discusses the iterative search procedure designed to minimize cask idle time in greater detail.

B. Definition of Variables

The Dantzig-Fulkerson model [11] requires three sets of input data. Using the terminology of the fuel cycle, the first requirement is a schedule of pickup times. Let PT denote the array of such pickup times where PT has the form depicted in Figure 4.1. Here, there are m sources, reactor sites, and n sinks, either reprocessing plants or spent-fuel disposal sites. In this array, pt_{ij}^{k} denotes the time at which the k^{th} load scheduled for delivery to sink j from source i must be packaged and transported.

The last two input requirements are m x n matrices which contain the load and travel times and the unload and travel times between each source and each sink. Define these matrices as A and B, respectively. Then, an element of A, a_{ij}, represents the time required to load a spent-fuel cask at the i^{th} reactor site and transport it to the j^{th} sink. Similarly, b_{ij}, an element of the matrix B, represents the time needed to unload a cask at the j^{th} sink and return to the i^{th} source.

This input data is used to construct an array of discharge times denoted by DT. In terms of the original input, the discharge time

Source	Sink 1	Sink 2	. . .	Sink m
1	$pt_{11}^{1}, pt_{11}^{2}, \ldots, pt_{11}^{n_1}$	$pt_{12}^{1}, pt_{12}^{2}, \ldots, pt_{12}^{n_2}$	. . .	$pt_{1m}^{1}, pt_{1m}^{2}, \ldots, pt_{1m}^{n_3}$
2	$pt_{21}^{1}, pt_{21}^{2}, \ldots, pt_{21}^{n_4}$	$pt_{22}^{1}, pt_{22}^{2}, \ldots, pt_{22}^{n_5}$	. . .	$pt_{2m}^{1}, pt_{2m}^{2}, \ldots, pt_{2m}^{n_6}$
.	.	.	. . .	.
.	.	.	. . .	.
.	.	.	. . .	.
m	$pt_{m1}^{1}, pt_{m2}^{2}, \ldots, pt_{m1}^{n_7}$	$pt_{m2}^{1}, pt_{m2}^{2}, \ldots, pt_{m2}^{n_8}$	. . .	$pt_{mm}^{1}, pt_{mm}^{2}, \ldots, pt_{mm}^{n_9}$

Figure 4.1

Format of input for the allocation model.

equals the pickup time plus the load and travel time to the indicated sink. Symbolically, $dt^k_{ij} = pt^k_{ij} + a_{ij}$. Then dt^k_{ij}, an element of the array DT, is the time at which the k^{th} cask loaded at reactor i for delivery to the j^{th} sink arrives at that destination. Two other quantities must be defined before the model can be formulated. Let $n_{\alpha i}$ represent the number of casks being loaded at reactor site i at time α and $N_{\beta j}$ be the number of casks arriving at sink j at time β. As defined, α varies from one to the maximum element of PT. Similarly, β ranges from one to the maximum element of the array of discharge times, DT.

C. Formulation of Constraints

The overall objective of the spent-fuel cask allocation model is to set up a delivery schedule for each required cask such that the number of required casks is minimized. Symbolically, this objective can be represented as the minimization of the sum of slack variables. Because these slack variables have no physical interpretation until the constraints of the model are formulated, the objective function will be considered after the formulation of the constraint set.

Before the constraints can be determined, the desired solution is examined. The final model solution must indicate a set of sequences of times, one sequence for each cask where each sequence is composed of monotonically increasing pickup times. One other restriction is placed upon the sequences of pickup times. It is not sufficient for the times to be only monotonically increasing. The time between loadings of a specific cask must be greater than or equal to the time required for that cask to be loaded at the first source indicated and travel to its destination plus the required time to unload at that desination and return to the next scheduled pickup location. This requirement becomes a constraint in the allocation model. Symbolically, suppose $t^{k_1}_{i_1 j_1}$ and $t^{k_2}_{i_2 j_2}$ are consecutive numbers in a cask schedule sequence. Because the sequences are monotonically increasing, $t^{k_1}_{i_1 j_1} < t^{k_2}_{i_2 j_2}$. Then the constraint becomes:

$$t^{k_2}_{i_2 j_2} - t^{k_1}_{i_1 j_1} \geq a_{i_1 j_1} + b_{i_2 j_1} \tag{4-1}$$

Let $x_{\alpha i \beta j}$ represent the number of reassignments from sink j at a time β to a reactor storage site i at time α. Using (4-1), if $b_{ij} > \alpha - \beta$ then $x_{\alpha i \beta j} = 0$. If the time required to unload at j and travel to i is greater than the difference between the two scheduling times, no reassignments for the given destination i can be made at the time β and be expected to arrive at time α. So $x_{\alpha i \beta j}$ must be zero for that combination of α, i, β, and j.

Several other restrictions are needed to adequately describe the transport situation. First,

$$\sum_{\alpha=1}^{\max PT} \sum_{i=1}^{m} x_{\alpha i \beta j} \leq N_{\beta j} \qquad \begin{array}{l} j = 1, 2, \ldots, n \\ \beta = 1, 2, \ldots, \max DT^{k}_{ij} \end{array} \tag{4-2}$$

This set of constraints ensures that no more casks are rerouted than are present. The total number of reassignments from sink j at time β

must be less than or equal to the number of casks arriving at sink j at time β.

Using the same reasoning, no more casks can be arriving at a reactor temporary storage site than are scheduled to load at that time. Symbolically,

$$\sum_{\beta=1}^{\max DT} \sum_{j=1}^{n} x_{\alpha i \beta j} \leq n_{\alpha i} \qquad \begin{array}{l} i = 1, 2, \ldots, m \\ \alpha = 1, 2, \ldots, \max PT_{ij}^{k} \end{array} \tag{4-3}$$

These constraints restrict the total number of arrivals to source i at time α due to reassignment to be less than or equal to the number of casks scheduled to be loaded at i at time α, for each combination of α and i. The number of reassignments must also always be nonnegative,

$$x_{\alpha i \beta j} \geq 0 \tag{4-4}$$

Thus the constraints of the model are:

$$\sum_{\alpha=1}^{\max PT} \sum_{i=1}^{m} x_{\alpha i \beta j} \leq N_{\beta j} \qquad \begin{array}{l} j = 1, 2, \ldots, n \\ \beta = 1, 2, \ldots, \max DT_{ij}^{k} \end{array}$$

$$\sum_{\beta=1}^{\max DT} \sum_{j=1}^{n} x_{\alpha i \beta j} \leq n_{\alpha i} \qquad \begin{array}{l} i = 1, 2, \ldots, m \\ \alpha = 1, 2, \ldots, \max PT_{ij}^{k} \end{array}$$

$$x_{\alpha i \beta j} \geq 0 \qquad \begin{array}{l} i = 1, 2, \ldots m \\ j = 1, 2, \ldots, n \\ \alpha = 1, 2, \ldots, \max PT_{ij}^{k} \\ \beta = 1, 2, \ldots, \max DT_{ij}^{k} \end{array}$$

where $b_{ij} > \alpha - \beta$ implies $x_{\alpha i \beta j} = 0$

D. Constraint Transformation

As presently written, the model constraints are not of the transportation type. Through the introduction of nonnegative slack variables, they can be transformed into a system of equalities.

Define $y_{\beta j}$ as the number of casks which arrive at sink j at time β and are not reassigned. Similarly, $z_{\alpha i}$ is the number of casks which begin their schedules at reactor storage site i with an initial pickup time at α. That is, $z_{\alpha i}$ is the number of casks beginning their schedules at source i having never been reassigned to i from some other location. These slack variables are required since a finite planning horizon is being employed. The casks have a specified end to their load schedule.

Adding these slack variables to the third and fourth systems of inequalities, constraints of the transportation type are obtained. The resulting constraints are:

$$\sum_{\alpha=1}^{\max PT} \sum_{i=1}^{M} x_{\alpha i\beta j} + y_{\beta j} = N_{\beta j} \qquad \begin{array}{l} \beta = 1, 2, \ldots, \max DT^k_{ij} \\ j = 1, 2, \ldots, n \end{array} \tag{4-5}$$

$$\sum_{\beta=1}^{\max DT} \sum_{j=1}^{n} x_{\alpha i\beta j} + z_{\alpha i} = n_{\alpha i} \qquad \begin{array}{l} \alpha = 1, 2, \ldots, \max PT^k_{ij} \\ i = 1, 2, \ldots, m \end{array} \tag{4-6}$$

$$y_{\beta j} \geq 0 \quad z_{\alpha i} \geq 0 \quad x_{\alpha i\beta j} \geq 0 \qquad \begin{array}{l} i = 1, 2, \ldots, m \\ j = 1, 2, \ldots, n \\ \alpha = 1, 2, \ldots, \max PT^k_{ij} \\ \beta = 1, 2, \ldots, \max DT^k_{ij} \end{array}$$

Because of the introduction of the slack variables, two additional constraints are required. First,

$$\sum_{\alpha=1}^{maxPT}\sum_{i=1}^{m} z_{\alpha i} + \sum_{\alpha=1}^{maxPT}\sum_{i=1}^{m}\sum_{\beta=1}^{maxDT}\sum_{j=1}^{n} x_{\alpha i\beta j} = \sum_{\alpha=1}^{maxPT}\sum_{i=1}^{m} n_{\alpha i} \tag{4-7}$$

This constraint ensures that the total number of casks loading at the reactor sites is equal to the number of casks loading at the beginning of their schedule plus the number of casks loading because of reassignment. Also,

$$\sum_{\beta=1}^{maxDT}\sum_{j=1}^{n} y_{\beta j} + \sum_{\alpha=1}^{maxPT}\sum_{i=1}^{m}\sum_{\beta=1}^{maxDT}\sum_{j=1}^{n} x_{\alpha i\beta j} = \sum_{\beta=1}^{maxDT}\sum_{j=1}^{n} N_{\beta j} \tag{4-8}$$

The total number of casks arriving at sinks must be the sum of those arriving for reassignment and those arriving at the end of their schedules.

E. Model Formulation

The primary objective of the model is to minimize the number of casks required to meet a given schedule. Because each cask must pick up its initial load at some source, this objective is equivalent to minimizing the sum of the slack variables $z_{\alpha i}$. An alternative objective function is the minimization of the sum of the $y_{\beta j}$ using the same logic.

As first formulated by Dantzig and Fulkerson, the final model in transportation form is:

$$\underset{(\overline{x},\overline{y},\overline{z})}{\text{minimize}} \sum_{\alpha=1}^{\max PT} \sum_{i=1}^{m} z_{\alpha i}$$

subject to:

$$\sum_{\alpha=1}^{\max PT} \sum_{i=1}^{m} x_{\alpha i \beta j} + y_{\beta j} = N_{\beta j} \qquad \begin{array}{l} j = 1, 2, \ldots, n \\ \beta = 1, 2, \ldots, \max DT^{i}_{ij} \end{array}$$

$$\sum_{\beta=1}^{\max DT} \sum_{j=1}^{n} x_{\alpha i \beta j} + z_{\alpha i} = n_{\alpha i} \qquad \begin{array}{l} i = 1, 2, \ldots, m \\ \alpha = 1, 2, \ldots, \max PT^{k}_{ij} \end{array}$$

$$\sum_{\alpha=1}^{\max PT} \sum_{i=1}^{m} z_{\alpha i} + \sum_{\alpha=1}^{\max PT} \sum_{i=1}^{m} \sum_{\beta=1}^{\max DT} \sum_{j=1}^{n} x_{\alpha i \beta j} = \sum_{\alpha=1}^{\max PT} \sum_{i=1}^{m} n_{\alpha i}$$

$$\sum_{\beta=1}^{\max DT} \sum_{j=1}^{n} y_{\beta j} + \sum_{\alpha=1}^{\max PT} \sum_{i=1}^{m} \sum_{\beta=1}^{\max DT} \sum_{j=1}^{n} x_{\alpha i \beta j} = \sum_{\beta=1}^{\max DT} \sum_{j=1}^{n} N_{\beta j}$$

$$y_{\beta j} \geq 0 \quad z_{\alpha i} \geq 0 \quad x_{\alpha i \beta j} >\geq 0 \qquad \begin{array}{l} \alpha = 1, 2, \ldots, \max PT^{k}_{ij} \\ i = 1, 2, \ldots, m \\ \beta = 1, 2, \ldots, \max DT^{k}_{ij} \\ j = 1, 2, \ldots, n \end{array}$$

where $b_{ij} > \alpha - \beta$ implies $x_{\alpha i \beta j} = 0$. Because maximum cask utilization is also an objective, an alternative formulation can be constructed using the same system of constraints but an objective function of:

$$\text{Maximize} \sum_{\alpha=1}^{\max PT} \sum_{i=1}^{m} \sum_{\beta=1}^{\max DT} \sum_{j=1}^{n} x_{\alpha i \beta j}$$

Since a reduction in the fleet of casks employed must result in an increase in cask utilization, the two formulations are equivalent.

The allocation model is of the transportation type with additional constraints so it can be solved using the Simplex Method with a standard Linear Programming Package. In this case, the number of computations required is reduced due to the large number of variables constrained to be zero. An alternative method of solution is to take advantage of the special structure of the model and use the transportation formulation. Then the objective function coefficient of each slack variable is unity as indicated above. One difference exists. Rather than explicitly treating the additional restrictions constraining variables to be zero, a big-M approach [24] could be used. By employing a large, positive objective function coefficient for these variables, they would be forced to zero as the objective function is minimized. The remaining variables would have a zero objective function coefficient as previously discussed. Regardless of the method employed, upon termination, the solution procedure indicates the values of the decision variables $z_{\alpha i}$, $y_{\beta j}$, and $x_{\alpha i \beta j}$ for each α, i, β, and j. These values are used to construct a feasible cask utilization schedule.

The slack variables $z_{\alpha i}$ represent the number of casks which begin their transport schedules at reactor sites i at times α. The expression

$$\sum_{\alpha=1}^{maxPT} \sum_{i=1}^{m} z_{\alpha i}$$

is the total number of transport casks required to meet the given delivery schedule. To construct a schedule for an individual cask, consider some $z_{\alpha i} > 0$. Let cask 1 begin its schedule at reactor storage site i at time α. Looking at the input array of pickup times, PT, some pt_{iw}^{k} must equal α. Assign cask 1 the transport of cargo from source i to sink w at time α. The scheduled arrival time β, which can be read from DT, is $\alpha + a_{iw}$. To find the next assignment of cask 1, consider values of $x_{\alpha' i \beta' w}$. If $x_{\alpha' i \beta' w}$ is positive, cask 1 must travel to reactor storage site i´ to pick up assembles at a time α'. This procedure continues until no $x_{\alpha' i \beta' w}$ is positive. At this point, the slack variable $y_{\beta w}$ will be positive indicating cask 1 has reached the end of its schedule. In this case, it will not be reassigned from sink w. This process is used to determine a schedule for each of the

$$\sum_{\alpha=1}^{maxPT} \sum_{i=1}^{m} z_{\alpha i} \quad \text{casks.}$$

F. <u>Iterative Search Technique</u>

A feasible transport schedule for the required casks is obtained using the allocation model. However, because this model's objective is solely to minimize the required number of transport casks, the obtained schedule is not necessarily an optimal one. In order to minimize the present worth of cask use cash flows, an iterative search technique can be applied to the feasible transport schedule obtained from the solution of the allocation model. This algorithm calculates idle time in each cask schedule and checks unoptimized cask schedules for feasible trips to occupy the idle time. Without altering the optimal number of casks, a schedule is obtained which indicates the optimal times of cask purchase or lease and a policy for the casks that minimizes the present worth of cask use costs.

Figure 4.2 is a simplified logic flow-chart of the search technique. In this figure, N is the minimum number of casks required to meet the fixed pickup schedule.

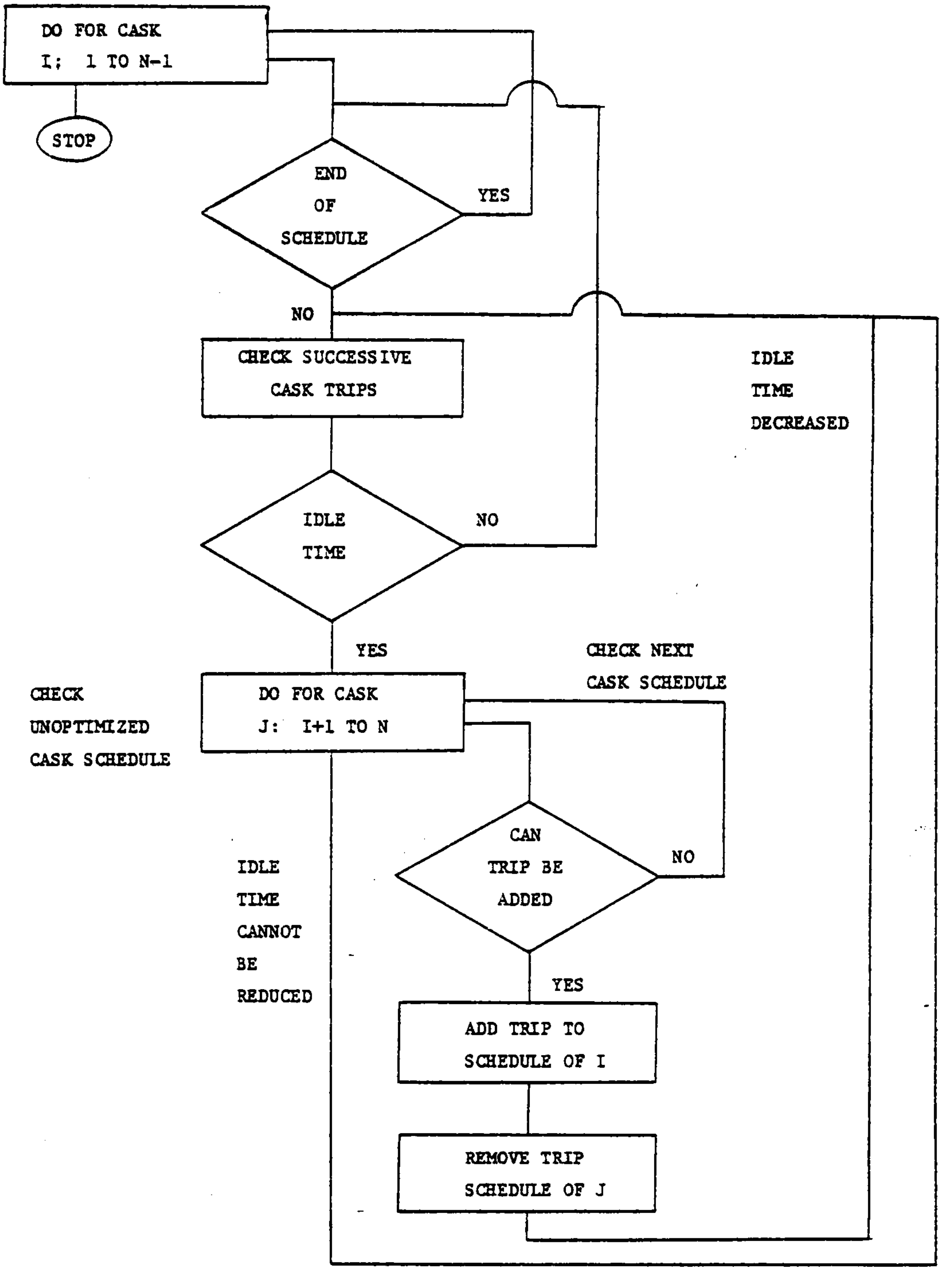


Figure 4.2

Flow chart: iterative search technique.

V. BASE CASE DEVELOPMENT

In this chapter, a hypothetical transport schedule is established and, using this information, optimal cask fleet sizes are determined for both the truck and the rail modes of transport. The formulation of this base case is established with two objectives: (1) to determine transportation requirements for the spent-fuel assemblies, and (2) to economically compare the transport alternatives of truck versus rail. In this base case analysis, those reactors refueled by the Babcock and Wilcox Corporation are used as sources for the discharged fuel assemblies. To develop the transport schedule, five possible spent-fuel destinations, including reprocessing plants and disposal sites, are assumed. These destinations include the two existing reprocessing plants located at West Valley, New York, and at Barnwell, South Carolina; one existing spent-fuel storage facility at Morris, Illinois; as well as one projected site at Oak Ridge, Tennessee; and another hypothetical site located at Hanford, Washington. The transport schedule encompasses a planning horizon from October, 1977, through December, 2000.

Before defining the input required for the base case, the underlying assumptions which form the basis of the case must be outlined. Three basic assumptions are common to both the truck and the rail models. First, because the present generation of spent-fuel transport casks are designed for short-term fuel cooling, the fuel assembly transport schedule assumes a 180 day reactor-basin storage period. Although this assumption does not necessarily reflect government decisions regarding spent-fuel disposition, such an assumption is feasible with respect to existing rail and truck transport casks. Second, regarding the spent-fuel destinations, facilities in West Valley, New York, Morris, Illinois, and Barnwell, South Carolina, are assumed to be presently capable of receiving spent-fuel shipments. The Oak Ridge, Tennessee, facility is assumed to come on line in October, 1986, while the facility in Hanford, Washington, becomes available in July, 1995. Third, the spent-fuel is always transported to the nearest on-line destination. Based upon these assumptions, a transport schedule is constructed by taking reactor refueling dates, adding a six month cooling period, and then shipping the discharged assemblies to the nearest available reprocessing or disposal site.

Because cask capacity is a function of the mode of transportation employed (and different properties characterize each mode of transport), the remaining underlying assumptions differ for each type of transport. For the truck model, the NFS-4 is assumed to be the employed transport cask design. This cask is capable of simultaneously transporting one Pressurized Water Reactor spent-fuel assembly with an approximate loaded cask weight of twenty-five tons [4]. Using the same truck transport estimate employed in the

Savannah River model [7], a transport speed of forty miles per hour is assumed. A twenty-four hour cask load time at the reactor site is used with a corresponding eighteen hour cask unload time [22].

For the rail model, the IF-300 is employed as representative of present rail cask design. This cask is designed to carry seven Pressurized Water Reactor spent-fuel assemblies with an approximate loaded cask weight of seventy-five tons [5]. Again using the Savannah River estimate [7], an average transport speed of seven miles per hour is used for the rail model. Cask load time is estimated at seventy-two hours while processing time at the cask destination is estimated to be forty-eight hours [22].

For the analysis of this base case, the values of the input parameters of the model as outlined in section B of Chapter IV must be defined. Using the data employed in the Savannah River model [7] fifteen Babcock and Wilcox reactors are designated as sources or pickup points. For reference ease, these sources are numbered consecutively and referred to by number in the remainder of this study. A complete listing of the fifteen sources and their reference numbers is given in Table 5.1. Similarly, each of the five destinations or sinks employed and their reference numbers are listed in Table 5.2.

For each of the fifteen sources, pickup dates, delivery points, and the number of casks required to pick up the shipment must be specified. To obtain this data, the recharge dates and the number of fuel assemblies required to recharge given in the Savannah River model [7] are used. Assuming that the same number of spent-fuel

Table 5.1

Base Case-Spent Fuel Sources

Reference number	Reactor	Location
1	Connecticut Yankee	Haddam Neck, Conn.
2	Greene County	Cementon, N.Y.
3	Three Mile Island	Goldsboro, Pa.
4	Erie	Berlin Heights, Ohio
5	Davis-Besse	Oak Harbor, Ohio
6	Midland	Midland, Mich.
7	Greenwood	St. Clair, Mich.
8	Central Iowa	Vandalia, Iowa
9	Pebble Springs	Arlington, Ore.
10	WNP 1,4	Richland, Wash.
11	Rancho Seco	Clay Station, Calif.
12	Ark	Russellville, Ark.
13	Bellefonte	Scottsboro, Ala.
14	North Anna	Mineral, Va.
15	Oconee	Seneca, S. C.

Table 5.2

Base Case Spent-Fuel Sinks

Reference number	Location
1	West Valley, N.Y.
2	Morris, Ill.
3	Barnwell, S.C.
4	Oak Ridge, Tenn.
5	Hanford, Wash.

assemblies are removed from the reactor as are added, the number of assemblies to be transported is obtained. The date of transport is determined by adding a six-month cooling period to the date of fuel removal from the reactor. That is, an assembly removed from a reactor in June is scheduled for transport in December of the same year. Because the model planning horizon encompasses a twenty-three year period, each month in the horizon is represented numerically as are the sources and the sinks. The months are numbered consecutively beginning with month 1 (October, 1977) and ending with month 276 (September, 2000).

To determine the number of casks required, the number of assemblies removed is divided by the cask capacity. When the result is non-integer and the reactor has just come on line, the result is rounded down. Otherwise, fractions are rounded up and a sufficient number of stored spent-fuel assemblies is transported to fill the cask. The delivery points are specified by shipping assemblies to the nearest available sinks. For example, shipments from the Belefont reactors would be to Barnwell, South Carolina, prior to October, 1986, and to Oak Ridge, Tennessee, after that date. Table 5.3 contains the mileage between each of the reactors and the sinks. Using this information, transport schedules for each of the sources can be specified. Table 5.4 contains a typical spent-fuel pick up schedule. The remaining schedules are listed in Appendix A. For each A(B) entry in these tables, A represents the pickup time while B is the number of casks required to transport the shipment.

Table 5.3

Base Case Mileage Chart

	Sink				
Source	1	2	3	4	5
1	448	759	555	576	2677
2	362	866	890	872	2805
3	262	702	682	653	2619
4	243	348	714	461	2211
5	288	296	753	463	2170
6	363	306	969	687	2302
7	305	300	896	609	2218
8	835	251	1173	811	1645
9	2679	1866	2684	2417	195
10	2641	1870	2648	2479	125
11	2652	2044	2783	2541	948
12	1101	640	882	583	2483
13	823	614	329	162	2382
14	515	821	502	409	2714
15	719	675	162	202	2643

Table 5.4

Typical Spent-Fuel Pick Up Schedule Rail Model

	Sink	
Source	3	4
13	58(9); 64(10); 70(10); 76(10); 82(10); 88(9); 94(10); 100(10); 106(10);	112(10); 118(9); 124(10); 130(10); 136(10); 142(10); 148(9); 154(10); 160(10); 166(10); 172(10); 178(9); 184(10); 190(10); 196(10); 202(10); 208(9); 214(10); 220(10); 226(10); 232(10); 238(9); 244(10); 250(10); 256(10); 262(9); 268(10); 274(10);
14	60(6); 67(7); 71(7); 78(7); 83(7); 90(7); 95(7); 102(6); 107(7);	114(7); 119(7); 126(7); 131(7); 138(7); 143(6); 150(7); 155(7); 162(7); 167(7); 174(7); 179(7); 166(6); 171(7); 178(7); 183(7); 190(7); 195(7); 202(7); 207(6); 214(7); 219(7); 266(7); 231(7); 238(7); 243(7); 250(6); 255(7); 262(7);

Notation: A(B);

A represents pickup time

B is the number of required casks to transport the shipment

Two other input requirements must be specified for each model. These are the 15 x 5 A and B matrices discussed in Section B of Chapter IV. The A matrix contains the times required to load a spent-fuel cask at a site and to transport it to some sink. Entry a_{ij} in the A matrix of the model is obtained using the formula:

$$a_{ij} = \left(\left(\frac{M_{ij}}{s} + l\right)/24 \text{ hrs/day}\right) (1/30 \text{ days/mth}) \tag{5.1}$$

where M_{ij} is the $(ij)^{th}$ entry of the mileage chart in Table 5.3, s is the average speed the cask is transported: seven miles per hour for rail casks or forty miles per hour for truck casks, and l is the load time at the reactor site: seventy-two hours for rail casks and twenty-four bours for truck casks. Table 5.5(a) contains the A matrix for the truck model while Table 5.5(b) contains the A matrix for the rail model. Entries in these tables are in months.

Similarly, the B matrix contains the time required to unload a cask at a sink and transport it to a reactor site. Each entry b_{ij} of the B matrix is calculated using formula 5.2:

$$b_{ij} = \left(\left(\frac{M_{ij}}{s} + \mu\right)/24 \text{ hrs/day}\right) (1/30 \text{ days/mth}) \tag{5.2}$$

Here μ represents the cask unload time at a sink, eighteen hours in the truck model or forty-eight hours in the rail model. The remaining terms are defined as in Equation 5.1. The B matrix for the truck case is given in Table 5.6(a) while that of the rail case is given in Table 5.6(b). A schedule of discharge times can be obtained by adding the load and transport time required to a given pick up time.

Table 5.5(a)

Truck A Matrix

Load and Travel Times (months)

	Sink				
Source	1	2	3	4	5
1	.049	.060	.053	.053	.127
2	.046	.063	.064	.064	.131
3	.042	.058	.057	.056	.124
4	.042	.045	.058	.049	.110
5	.043	.044	.059	.049	.109
6	.046	.044	.067	.057	.113
7	.045	.044	.064	.054	.110
8	.062	.042	.074	.062	.090
9	.126	.098	.127	.117	.040
10	.125	.098	.125	.119	.038
11	.125	.104	.129	.122	.066
12	.072	.056	.064	.054	.119
13	.062	.045	.039	.039	.116
14	.051	.051	.048	.048	.128
15	.058	.057	.039	.040	.125

Table 5.5(b)

Rail A Matrix

Load and Travel Times (months)

	Sink				
Source	1	2	3	4	5
1	.189	.251	.210	.214	.631
2	.172	.272	.277	.273	.657
3	.152	.239	.235	.230	.620
4	.148	.169	.242	.191	.539
5	.157	.159	.249	.192	.531
6	.172	.161	.292	.236	.557
7	.161	.159	.278	.221	.540
8	.266	.150	.333	.261	.426
9	.632	.470	.633	.580	.139
10	.624	.471	.625	.592	.125
11	.626	.506	.652	.604	.288
12	.318	.227	.275	.216	.593
14	.202	.263	.1996	.181	.638
15	.243	.234	.132	.140	.624

Table 5.6(a)

Truck B Matrix

Matrix of Unload and Travel Time

	Sink				
Source	1	2	3	4	5
1	.041	.051	.044	.045	.118
2	.038	.055	.056	.055	.122
3	.034	.049	.048	.048	.116
4	.033	.037	.050	.041	.102
5	.035	.035	.051	.041	.100
6	.038	.036	.059	.049	.105
7	.036	.035	.056	.046	.102
8	.054	.034	.066	.053	.082
9	.118	.089	.118	.109	.032
10	.117	.090	.117	.111	.029
11	.117	.096	.122	.113	.058
12	.063	.047	.056	.045	.111
13	.053	.046	.036	.031	.108
14	.043	.054	.042	.039	.119
15	.050	.048	.031	.032	.117

Table 5.6(b)

Rail B Matrix

Matrix of Unload and Travel Time

	Sink				
Source	1	2	3	4	5
1	.156	.217	.177	.181	.598
2	.138	.238	.243	.240	.623
3	.119	.206	.202	.196	.586
4	.115	.136	.208	.158	.505
5	.124	.125	.216	.158	.497
6	.139	.127	.259	.203	.523
7	.127	.126	.244	.188	.507
8	.232	.117	.299	.228	.393
9	.598	.437	.599	.546	.105
10	.591	.438	.592	.558	.091
11	.593	.472	.619	.571	.255
12	.285	.194	.242	.182	.559
13	.230	.188	.132	.099	.539
14	.169	.229	.166	.148	.605
15	.209	.201	.099	.107	.591

With all the necessary input data defined, the minimum number of casks for each mode of transportation and an optimal schedule for each cask can be obtained. Based upon these optimal schedules, the alternative transport modes can be economically compared. Figure 5.1 illustrates the solution procedure employed to accomplish these objectives. Five computer codes are required. The first code, programmed in PL/1, is developed to write data on a magnetic tape. Because the allocation model formulation of the base case consists of 89,400 variables and 821 constraints, this code is ued to generate all input data. The data generated by the PL/1 code is in the format required for input to the second code. This second code, a Mathematical Programming System Extended III (MPS X III) Code [25], is employed to solve the formulated truck and rail mathetmatical models. These formulations differ only in right hand side elements. After solving the truck model formulation, the optimal basis obtained is specified as an initial basis for the rail model. Using this procedure, the rail solution is obtained immediately.

The last three computer codes are all programmed in Fortran. The third code, programmed in Fortran G, is designed to determine feasible cask schedules based upon the MPS X III code results. These schedules are used as input for the fourth code programmed in Fortran H. This code is an iterative search procedure which optimizes the cask schedules with respect to cask idle time. The last computer code is designed to economically compare the optimal truck and rail modes

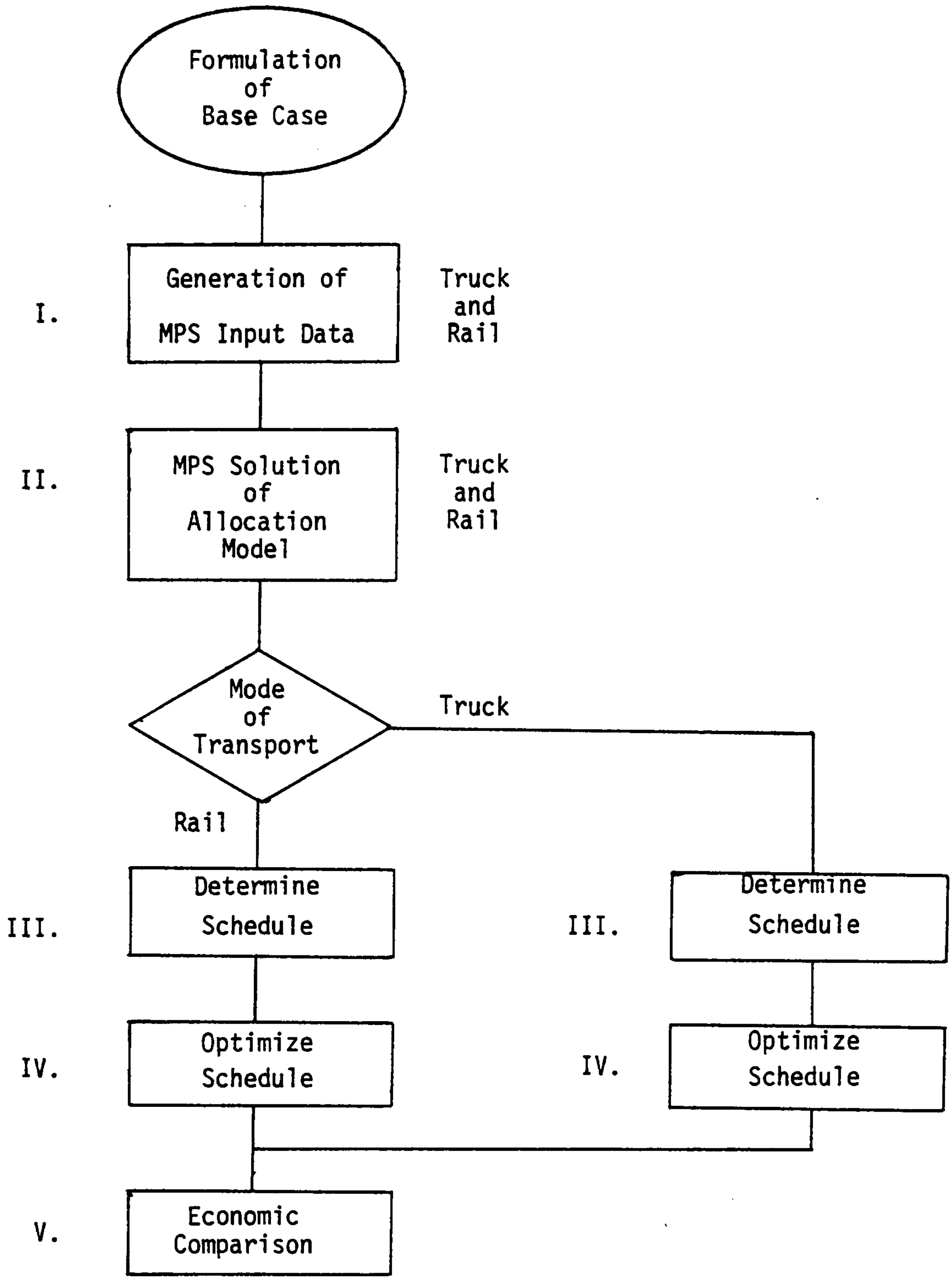


Figure 5.1

Solution procedure.

of transport based upon the schedules obtained from the iterative search procedure. All computer codes and complete logic developments are included in Appendix B.

VI. RESULTS

The model of Dantzig and Fulkerson [11], the allocation model, is used to determine the minimum number of required spent-fuel casks for the base case transport situation defined in Chapter V. When rail transport is employed, the results indicate that a minimum of 55 rail casks are required. Because of the reduced capacity of truck casks, a minimum of 384 casks are needed to meet the same pickup schedule when transporting by truck.

An analysis of the effects of varying reprocessing or disposal site availability dates is performed. For the base case, the transport destination at Oak Ridge, Tennessee, is assumed to start up in October, 1986 while the site at Hanford, Washington, is not to be functional until July, 1995. As these availability dates are varied, the number of required casks is not affected even when the Oak Ridge and Hanford sites are not incorporated at all. A similar variance of availability dates for the Morris, West Valley, and Barnwell sites yields the same result. As presently formulated, the model is not sensitive to destination locations.

Although indicating the minimum number of required casks, a feasible schedule for these casks is not directly available from the solution of the allocation model. As discussed in Chapter IV, basic variables which are not slack variables can be employed to determine a feasible schedule. Using the computer code in Appendix B, a schedule for each required cask in both the rail and truck models is obtained. Table 6.1 contains the complete schedule of rail cask 33. This is an example taken from the results. There are 384 truck schedules and 55 rail schedules [26]. For each T (i, j) = α entry, i represents the pickup site, j represents the destination site and α represents the pickup time. For example, the second trip of cask 33 begins when spent fuel is picked up from site 11; Rancho Seco, at time 39; December, 1980, for delivery to destination 2; Morris, Illinois.

Tables 6.2 and 6.3 summarize the cask operational statistics which characterize the schedule indicated by the allocation model. Any cask which begins its schedule in a year is assumed to come on line in that year. Similarly, any cask which completes its schedule in a particular year retires in that year. The number of casks in use in year i equals the sum of the casks required in years 1 through i minus the sum of the number of casks retired in years 1 through i. At the end of the 23 year planning horizon, all casks are retired. The utilization factor is found by dividing the actual number of trips in a given year by the maximum possible number of trips in that year.

Although the cask schedules obtained from the allocation model [11] are feasible, the casks are not necessarily used to best advantage. In order to minimize cask idle time, an iterative search technique is applied to the feasible solution obtained from the

Table 6.1

Schedule for Rail Cask 33: Allocation Model

T (1, 1) = 33; T (11, 2) = 39; T (12, 2) = 43; T (15, 3) = 49; T (12, 2) = 55;
T (15, 3) = 61; T (3, 1) = 66; T (12, 2) = 67; T (15, 3) = 73; T (3, 1) = 78;
T (12, 2) = 79; T (15, 3) = 85; T (13, 3) = 88; T (10, 2) = 89; T (14, 3) = 95;

T (15, 3) = 97; T (11, 2) = 99; T (15, 3) = 101; T (3, 1) = 102; T (6, 2) = 107;
T (5, 1) = 112; T (3, 1) = 118; T (8, 2) = 123; T (13, 4) = 124; T (10, 2) = 125;
T (13, 4) = 130; T (15, 3) = 131; T (8, 2) = 135; T (5, 1) = 136; T (15, 3) = 137;

T (14, 4) = 138; T (6, 2) = 143; T (11, 2) = 147; T (10, 2) = 149; T (3, 1) = 150;
T (6, 2) = 155; T (15, 3) = 157; T (8, 2) = 159; T (5, 1) = 160; T (10, 2) = 161;
T (9, 2) = 163; T (9, 2) = 175; T (5, 1) = 180; T (7, 2) = 183; T (9, 2) = 186;

T (6, 2) = 191; T (4, 1) = 196; T (10, 2) = 197; T (15, 3) = 205; T (8, 2) = 207;
T (5, 1) = 208; T (15, 3) = 209; T (3, 1) = 210; T (2, 1) - 212; T (15, 3) = 217;
T (13, 4) = 220; T (2, 1) = 224; T (7, 2) = 231; T (13, 4) = 232; T (9, 5) = 235;

T (15, 3) = 241; T (1, 1) = 243; T (3, 1) = 246; T (14, 4) = 250; T (5, 1) = 252;
T (15, 3) = 253; T (13, 4) = 256; T (8, 2) = 267; T (4, 1) = 268; T (9, 5) = 271;
T (7, 2) = 279.

Notation: T (i, j) = α;

i represents pickup point reference number

j represents delivery point reference number

α represents pickup time reference number

Table 6.2

Rail Cask Operational Statistics: Allocation Model

Year	Number of New Casks Required	Number of Casks Retired	Number of Casks in Use	Utilization Factor
1	24	0	24	.18
2	8	0	32	.16
3	8	0	40	.14
4	10	0	50	.13
5	3	0	53	.15
6	2	0	55	.20
7	0	0	55	.24
8	0	0	55	.21
9	0	0	55	.27
10	0	0	55	.31
11	0	0	55	.33
12	0	0	55	.33
13	0	0	55	.36
14	0	0	55	.37
15	0	0	55	.37
16	0	0	55	.35
17	0	0	55	.38
18	0	0	55	.36
19	0	0	55	.35
20	0	0	55	.36
21	0	0	55	.36
22	0	0	55	.36
23	0	55	0	.50

Table 6.3

Truck Cask Operational Statistics: Allocation Model

Year	Number of New Casks Required	Number of Casks Retired	Number of Casks in Use	Utilization Factor
1	138	0	138	.22
2	52	0	190	.18
3	58	0	248	.15
4	63	0	311	.14
5	48	0	359	.15
6	16	0	375	.20
7	9	0	384	.23
8	0	0	384	.21
9	0	0	384	.27
10	0	0	384	.32
11	0	0	384	.34
12	0	0	384	.33
13	0	0	384	.35
14	0	0	384	.37
15	0	0	384	.38
16	0	0	384	.36
17	0	0	384	.37
18	0	0	384	.36
19	0	0	384	.35
20	0	0	384	.36
21	0	0	384	.36
22	0	0	384	.36
23	0	384	0	.42

allocation model solution. Using the same notation as that employed in Table 6.1, the new schedule of rail cask 33 is presented in Table 6.4. Whereas cask 33 began its schedule in June, 1980, according to the intermediate solution obtained from the allocation model, in the final schedule it does not come on line until January, 1987.

Tables 6.5 and 6.6 contain the cask operational statistics which characterize the schedules obtained from the iterative search procedure. Compared with the results of the allocation model summarized in Tables 6.2 and 6.3, the casks now come on line in a more staggered fashion. Similarly, the casks retire before the end of the planning horizon rather than simultaneously in the last year. In addition to these changes, the utilization factor is higher in each year for the final result than for the corresponding years in the intermediate result of the allocation model [11]. Also, on estimated present worth net savings of $56,634,400 results by employing the improved truck schedule for the planning horizon rather than using the truck schedule obtained from the allocation model. This result is based upon the truck transport, cask purchase alternative of the economic model developed in the remainder of this chapter.

The costs incurred by employing the indicated number of spent fuel casks and by following the obtained schedule are determined neither by the allocation model nor by the search procedure. In order to determine these associated costs, a transport policy must be defined. Three characteristics form the basis of such a transport policy. First, the mode of transport, truck or rail, must be specified.

Table 6.4

Schedule for Rail Cask 33: Iterative Search Technique

T (13, 4) = 112; T (11, 2) = 123; T (5, 1) = 124; T (14, 4) = 131; T (11, 2) = 135;
T (5, 1) = 136; T (11, 2) = 147; T (5, 1) = 148; T (14, 4) = 150; T (8, 2) = 159;
T (5, 1) = 160; T (14, 4) = 162; T (11, 2) = 171; T (5, 1) = 172; T (15, 3) = 173;

T (14, 4) = 174; T (11, 2) = 183; T (5, 1) = 184; T (9, 2) = 186: T (11, 2) = 195;
T (5, 1) = 196; T (11, 2) = 207; T (5, 1) = 208; T (15, 3) = 209; T (11, 5) = 219;
T (5, 1) = 220; T (11, 5) = 231; T (5, 1) = 232; T (8, 2) = 243; (T (5, 1) = 244;

T (11, 5) = 255; T (5, 1) = 256; T (15, 3) = 257; T (11, 5) = 267; T (5, 1) = 268;
T (11, 5) = 279;

Notation: T (k, j) = α;

i represents pickup point reference number

j represents delivery point reference number

α represents pickup time reference number

Table 6.5

Rail Cask Operational Statistics: Iterative Search Technique

Year	Number of New Casks Required	Number of Casks Retired	Number of Casks in Use	Utilization Factor
1	17	0	17	.26
2	0	0	17	.29
3	0	0	17	.33
4	0	0	17	.39
5	0	0	17	.45
6	6	0	23	.48
7	5	0	28	.47
8	0	0	28	.42
9	0	0	28	.53
10	8	0	36	.49
11	10	0	46	.42
12	0	0	46	.39
13	0	0	46	.43
14	0	0	46	.44
15	1	0	47	.44
16	8	1	54	.37
17	0	1	53	.39
18	0	0	53	.37
19	0	0	53	.37
20	0	0	53	.38
21	0	7	46	.37
22	0	0	46	.43
23	0	46	0	.59

Table 6.6

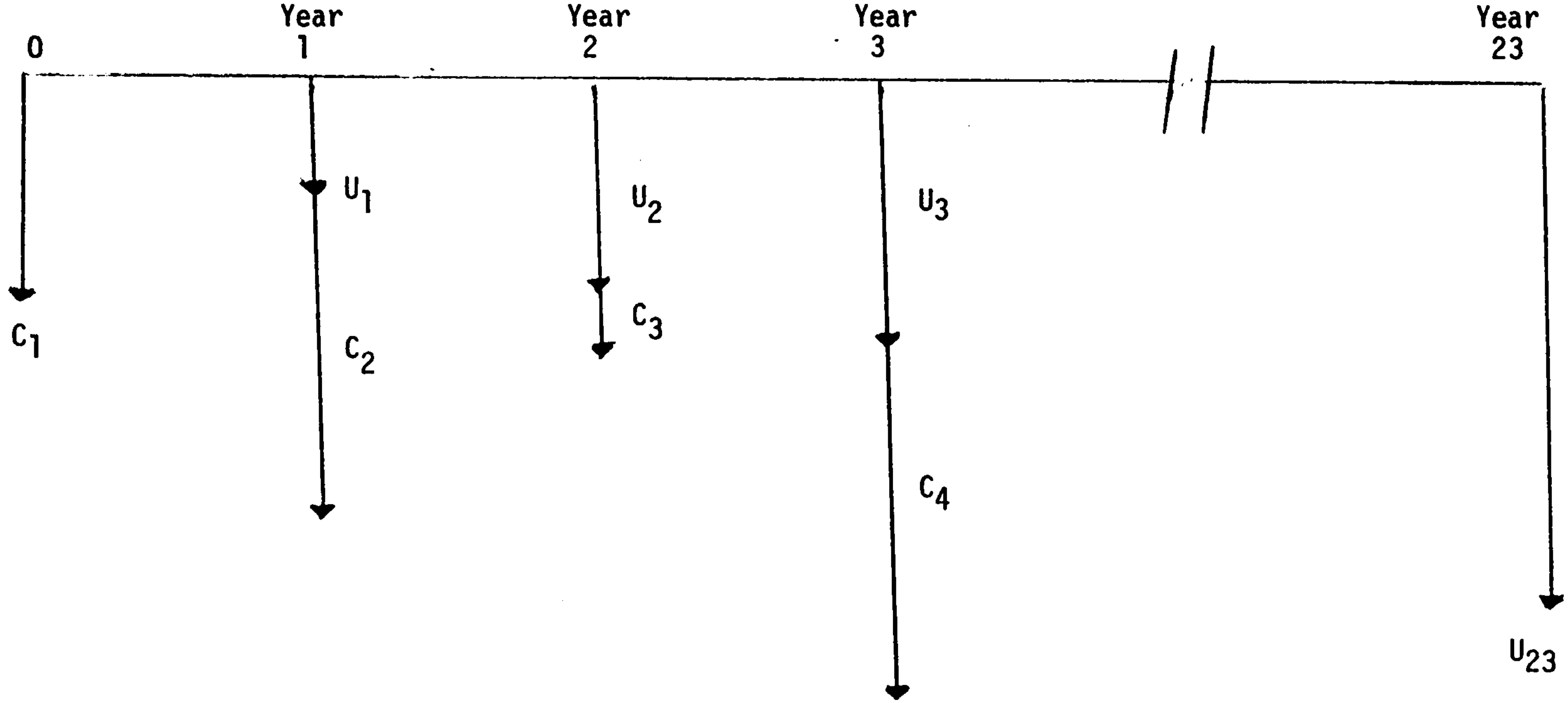
Truck Cask Operational Statistics: Iterative Search Technique

Year	Number of New Casks Required	Number of Casks Retired	Number of Casks in Use	Utilization Factor
1	113	0	113	.26
2	0	0	113	.30
3	0	0	113	.34
4	0	0	113	.40
5	12	0	125	.43
6	40	0	165	.46
7	32	0	197	.45
8	0	0	197	.41
9	1	0	198	.52
10	56	0	254	.48
11	69	0	323	.41
12	3	0	326	.39
13	0	0	326	.41
14	0	0	326	.43
15	1	0	327	.44
16	47	0	374	.37
17	10	22	362	.39
18	0	0	362	.38
19	0	0	362	.37
20	0	0	362	.38
21	0	39	323	.38
22	0	0	323	.43
23	0	323	0	.50

The second criteria, applying only to rail transport, is the type of transportation used--the use of regular freight as opposed to the employment of dedicated trains. The third option relates to cask procurement--the alternatives of cask purchase versus cask lease. Using these characteristics, six alternatives are compared with respect to cost: the truck, purchase option; the truck, lease option; the rail, purchase option with regular freight; the rail, lease option with regular freight; the rail, purchase option with dedicated trains; and the rail, lease option with dedicated trains.

The incurred costs are approximated under four restrictions. First, casks required for use in a particular year are assumed to be obtained at the end of the previous year. Second, casks retiring in a year are assumed to retire at the end of that year. Without these assumptions, casks which begin and end their schedules in the same year would not be considered in the economic analysis. Third, leased casks must be leased on a monthly basis. Because the units of the allocation model are months, cask lease on a daily basis is meaningless for this model. Finally, all costs incurred during the course of a year except those resulting from leasing or purchasing casks are assumed to occur at the end of that year. Figure 6.1 illustrates the incorporation of these assumptions into an economic model.

Although six alternatives are compared, only two distinct models are required. The first model covers those policies which involve the purchase of casks while the second applies to those which specify cask lease. In the purchase model, costs are incurred due



C_i: Cost of obtaining casks for use in year i

U_i: Transport costs incurred in year i

Figure 6.1. Cash flow diagram of costs incurred during the base case 23 year planning horizon.

to cask purchase and due to yearly cask use. When purchasing casks, the cost incurred is proportional to the number of casks purchased and is given by

$$N_{i+1} * CC \tag{6.1}$$

where N_{i+1} represents the number of casks to be purchased for use in year i + 1 and CC is the unit cost of a spent-fuel cask. As previously discussed, the casks purchased in year i are those required for use in year i + 1. To estimate the cost incurred during year i resulting from the transport of spent fuel casks, three cost components are considered: freight costs, FC; material handling costs, MC; and surcharges, S, incurred when using dedicated trains. Assuming these costs are expressed in units of dollars per ton mile, the cost due to the use of casks in year i can be expressed as

$$(FC + MC + S) * TM_i * WT \tag{6.2}$$

where TM_i is the total number of miles traveled in year i and WT is the loaded cask weight in tons. Combining equations 6.1 and 6.2, the total cost incurred in year i is

$$(N_{i+1} * CC) + (FC + MC + S) * TM_i * WT \tag{6.3}$$

Based upon equation 6.3, the costs incurred in purchasing casks during the twenty-three year base case planning horizon is

$$(N_1 * CC) + \sum_{i=1}^{23} [(N_{i+1} * CC) + (FC + MC + S) * TM_i * WT] * d_i. \tag{6.4}$$

Equation 6.4 gives costs in 1977 dollars where d_i represents the discount factor employed to obtain present worth. When evaluating alternatives specifying the use of regular freight rather than the use of dedicated trains, the surcharge S is zero. Also, the unit cask cost, the number of casks purchased each year, the total number of miles traveled, and the loaded cask weight varies depending upon the mode of transport.

When considering the cask lease option, only one cost differs. Because the casks are not purchased but are leased, the cost of leasing is a function of the number of times the casks are used rather than just the number of casks required. Because a cask must be leased for each trip in year i, the cost incurred due to leasing in year i is proportional to the number of trips in year i. This cost is given by

$$TR_i * LR * 30 \qquad (6.5)$$

where TR_i is the total number of trips in year i, LR is the cask lease rate per day, and a conversion figure of 30 days per month is used. Then, when leasing casks, the total cask cost for the base case in 1977 dollars is

$$TR_1 * LR * 30 + \sum_{i=1}^{23} [(TR_{i+1} * LR * 30) + (FC + MC + S) * TM_i * WT] * d_i \qquad (6.6)$$

As previously discussed, no surcharge is required unless dedicated trains are employed.

Tables 6.7 and 6.8 contain the number of trips per year and the total mileage traveled each year for the rail and truck schedules as obtained from the iterative search procedure. In addition, Table 6.8 contains the discount factors based upon an interest rate of fifteen percent. Table 6.9 contains the cost data used in the economic comparison. Values in this table are taken from an analysis conducted by the E. I. DuPont de Nemours and Company [23]. Where required, the data is converted to units of dollars per ton mile. For example, the DuPont report uses a surcharge cost of \$12,100,000 per year. Based upon an \$18/(mile) (train) surcharge, this cost is derived for the base case. This base case consists of 670 cask trips per year, each averaging 1000 miles per trip with an assumed cask weight of 85 tons. Then, the yearly surcharge cost is:

$$\frac{\$18}{\text{mile train}} * \frac{\text{train}}{\text{1 cask}} * \frac{\text{1000 miles}}{\text{trip}} * \frac{\text{670 cask trips}}{\text{year}}$$

$$= \$12.1 \times 10^6 \text{ per year}$$

This value can be converted to an equivalent dollar/ton mile cost as follows

$$\frac{\$12.1 \times 10^6}{\text{year}} * \frac{\text{year}}{\text{670 trips}} * \frac{\text{trip}}{\text{1000 miles}} * \frac{1}{\text{85 tons}}$$

$$= \$.0213/\text{ton mile}$$

Other values are converted to units of dollars per ton mile in the same manner. It should be noted that a breakdown of operating costs between rail and truck cask receipt is not performed. This is because those costs are based upon the number of work crews employed. This cost has been accounted for in the material handling value [23].

Table 6.7

Rail Cask Schedule Characteristics

Year	Number of Miles Traveled	Number of Trips per Year
1	94343	53
2	87727	60
3	54569	67
4	107014	80
5	112904	92
6	195034	133
7	210566	157
8	228272	141
9	254409	178
10	301478	210
11	318205	230
12	304272	216
13	365603	234
14	364083	242
15	360199	250
16	356676	242
17	370501	248
18	342164	235
19	330178	232
20	335174	239
21	310779	235
22	328664	240
23	287553	325

Table 6.8

Truck Cask Schedule Characteristics and Discount Factors

Year	Number of Miles Traveled	Number of Trips per Year	Discount Factors
1	634044	356	0.8696
2	588623	404	0.7561
3	373269	458	0.6575
4	721742	538	0.5718
5	774510	641	0.4972
6	1346531	920	0.4323
7	1451338	1072	0.3759
8	1578772	977	0.3269
9	1780658	1244	0.2843
10	2123401	1458	0.2472
11	2191988	1579	0.2149
12	2125473	1523	0.1869
13	2524738	1609	0.1625
14	2561116	1697	0.1413
15	2501871	1739	0.1229
16	2477714	1665	0.1069
17	2555548	1726	0.0929
18	2401303	1640	0.0808
19	2266573	1616	0.0703
20	2275643	1650	0.0611
21	2199734	1642	0.0531
22	2261172	1666	0.0462
23	1973946	1914	0.0402

Table 6.9

Input Data: Economic Model

	Rail Model	Truck Model
Loaded Cask Weight	75 tons	25 tons
Purchase Cost	\$1,300,000	\$500,000
Lease Cost	\$3000/day	\$650/day
Freight Cost	8¢/ton mile	8¢/ton mile
Dedicated Train Surcharge	\$.0213/ton mile	-----
Material Handling Cost	\$0135/ton mile	\$.0178/ton mile
Cask Capacity	7 PWR/18 BWR	1 PWR/2 BWR

Using the input data in Table 6.9, the total costs incurred by employing each of the six previously outlined transport policies for the base case are calculated. By dividing this cost by the total number of assemblies transported and by the total number of miles traveled, cost data in units of dollars per assembly mile are obtained. Table 6.10 summarizes the results.

An equivalent future worth analysis (costs in 2000 dollars rather than in 1977 dollars) is obtained by multiplying these values by a constant $(1 + i)^n$. In this constant, i is the interest rate employed, fifteen percent, and n is the number of years involved--twenty-three. The relative difference between values is preserved. Table 6.11 summarizes the results of the economic analysis in year 2000 dollars.

Table 6.10

Results of Economic Comparison

($/assembly mile:

1977 dollars)

	Purchase Option	Lease Option
Truck Regular Freight	2.79	3.50
Rail Regular Freight	1.05	2.20
Rail Dedicated Train	1.10	2.25

Table 6.11

Results of Economic Comparison

($/assembly mile:

2000 dollars)

	Purchase Option	Lease Option
Truck Regular Freight	69.45	87.12
Rail Regular Freight	26.14	54.76
Rail Dedicated Train	27.38	56.00

VII. CONCLUSIONS AND RECOMMENDATIONS

It is concluded that the transport of irradiated fuel assemblies, subject to a fixed pick up schedule, can be modeled as a transportation problem with additional constraints. This model can be solved to identify the minimum number of required transport casks as well as to provide sufficient information to determine a feasible schedule for the required casks. From this feasible schedule, an improved schedule which minimizes transport cask idle time is obtained through the use of an iterative search procedure.

By varying the availability dates of potential cask destinations, it is found that the model is not sensitive to the dates upon which disposition sites become functional. Variation of availability dates has the effect of also varying disposition locations. The model assumes spent-fuel assemblies are transported to the nearest available disposal site. By examining the effects of postponing sink operational dates, the distance traveled from source to sink becomes greater than that in the base case. When an operational date is advanced, less distance must be transversed than in the base case. Then, the model lack of sensitivity to sink availability dates also reflects upon the model sensitivity to distance traveled in terms of cask requirements. The lack of effect resulting from this variance implies that the number of casks in the transport fleet is dependent upon the quantity of assemblies to be transported rather than upon their eventual disposition sites.

Two properties of the model formulation seem to foster the model insensitivity to variance in availability date. First is the comparatively large time units of the pickup schedule. Trips are scheduled in units of months while travel time requires a maximum of only three weeks. Because of the slack time involved, even when the required mileage is increased, the indicated cask fleet can meet the pickup schedule. The corresponding idle-time in the base case solution is just reduced. The second factor which may foster this insensitivity is the assumption that the spent fuel is always transported to the nearest sink. This assumption keeps the travel time small and results in few infeasible schedule combinations. When greater travel times are used for more trips, the solution must change.

From the iterative search procedure, it is found that the cask fleet will grow as additional reactors become operational. In the rail model, seventeen casks are required initially and this number is sufficient to meet all demand in the first five years. In the sixth year, additional casks are required due to increased demand. The truck model follows a similar pattern.

Although the results of the iterative search procedure yield schedules more efficient than those obtained by the allocation model, the utilization percentages remain deceptively low. In fact, the utilization factors cited are the greatest lower bounds upon the true utilization percentages. This is because utilization is estimated as the number of trips made in a year divided by the maximum possible number of trips in that year, i.e., the number of casks on-line in that year multiplied by twelve. In reality, this divisor is an upper bound on the number of possible cask trips. If trips are scheduled for each month of the year in sufficient quantity to keep all casks occupied, then the divisor is accurate. However, in some months no trips are scheduled. Second, a cask which may end its schedule in the first month of a year is considered to be on-line for the entire year. Then, although the cask has actually retired, its idleness affects the utilization factor. By removing the casks from consideration as they retire, the utilization factors become greater.

As indicated by the results of the economic comparison, rail transport is more economically attractive than truck transport. Using the present worth values, the use of rail transport results in a savings of $1.74/assembly mile for the purchase option and of $1.30/ assembly mile when casks are leased. For the entire 23 year planning horizon, the utilization of rail casks results in a net savings of $72,203,301 for the purchase option and of $52,984,360 for the lease option. When dedicated trains are employed, the economic advantage of rail over truck transport decreases to $1.69/assembly mile for the purchase option and to $1.25/assembly mile for the lease option. This corresponds to net savings of $70,117,413 for the purchase option and of $50,898,500 for the lease option. Although it is not possible to compare actual results because of the different units employed, the economic analysis made by the E. I. DuPont de Nemours Company indicates the same general conclusion [23]. Rail transport is more economically attractive than the transport of spent fuel assemblies by truck.

Two reactors used in this study do not have rail access at the reactor site. The Connecticut Yankee plant is located ten miles from the nearest railhead while the Oconee plant is six miles from a railhead [5]. The cost of rail construction to these sites has not been incorporated into the economic comparison. Rather, each site is assumed to have rail access. This assumption is employed because the utilities with rail access should not be charged for the construction required for those without access. Second, even though rail transport is more attractive on a per assembly mile basis, those utilities without rail access may lack the capital necessary for the major project of constructing railroads [5].

With respect to the purchase versus lease options, the economic comparison indicates a savings of $.71/assembly mile of purchase over lease option for the truck case and a savings of $1.15/assembly mile for the rail case. In terms of net savings over the entire planning horizon, results indicate a savings of $29,261,400 for the truck case and a savings of $48,480,341 for the rail case when transport casks are purchased rather than leased. However, the estimated cost associated with the lease option is inflated. In reality, spent-fuel casks are leased on a daily basis. Because schedule pickup times are in months for the base case, it is assumed that each cask must be leased for a minimum of one month even though it may complete its task in a fraction of that time. For this reason, the lease charges incorporated into the model may be greater than those which would actually be incurred.

Based upon the results of the allocation model and of the iterative search technique, this study projects a scenario of cask demand. For the twenty-three year planning horizon of the base case, 384 truck casks or 55 rail casks are required to meet the given pickup schedule. In the first year of the planning horizon, 113 truck casks or 17 rail casks are needed. At present, insufficient casks exist to meet this demand. There is currently a total of sixteen casks in the United States which are capable of transporting spent light water reactor fuel [5]. Twelve of these are truck casks while the remaining four are for rail transport. Projections of required design, licensing, procurement, and fabrication time indicate a three year lead time for legal weight truck casks [5]. This value jumps to six years for a rail cask [5]. Due to these large lead times and the present cask shortage, the availability of spent-fuel shipping casks is a factor which must be addressed immediately to insure an adequate supply of transport casks. Neglecting political uncertainties, the results point out the need to construct rail spent-fuel casks for the transport of irradiated fuel assemblies.

There are several areas of future study which are of interest for extending this analysis of the transport of irradiated fuel assemblies. Another analysis using smaller time units and a more realistic disposition site assignment rule could be used to determine transportation fleet size as a function of the number, location, and availability dates of eventual spent-fuel sinks. A model incorporating mixed strategies that include the use of both truck and rail transport would offer insight concerning the costs involved for those sites which lack rail access but which are served by the cask fleet.

Another area of interest is the use of penalty functions to model the transport environment. As the model is presently formulated, the fixed pickup schedule must be met. For this reason, one rail cask comes on-line to make a single trip and then retires. Although a penalty cost would be incurred by missing this pickup deadline, this cost could be less than that resulting from obtaining an additional cask. By modeling the problem with penalty functions, such trade-offs could be explicitly considered.

The present solution procedure also oversimplifies cask utilization. The search procedure developed for this analysis checks schedules in an effort to prevent idle time whenever possible. However, it does not consider the trade-off between cask idle time and distance traveled. In order to minimize the distance traveled as well as cask idle time, a double criterion could be used. For example, when a cask is idle, all feasible trips scheduled for other unoptimized cask schedules which would fill the idle time are candidates to be added to the cask's schedule. Then, that trip which involves the least distance from the last cask location would be the trip added to the cask schedule being optimized. Employing this dual criterion would result in a schedule which minimizes distance traveled as well as cask idle time.

With respect to the economic comparison, a more precise analysis of the cask purchase versus lease options is required. An analysis of barge transport and the associated cost on a per assembly mile basis is also needed.

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IX. APPENDIXES

A. Base Case Input Data

B. Computer Codes

APPENDIX A

Base Case Input Data

The data presented in Tables A.1-A.11 constitute the pickup schedule for the rail and truck casks used in the base case analysis. The notation employed is identical to that of Table 5.4. For each A(B) entry, A represents the pickup time while B is the number of casks required to transport the spent fuel.

Notation applicable to tables in this appendix: A(B);

A represents pickup time

B is the number of required casks to transport the shipment

Table A.1

Base Case Pick Up Schedule: Rail Model

Source	Sink 1
1	5(8); 19(8); 33(8); 47(8); 61(8); 75(8); 88(8); 103(8); 117(8); 131(8); 145(8); 159(8); 173(8); 186(8); 201(8); 215(8); 229(8); 243(8); 257(8); 271(8);
2	82(9); 102(10); 114(10); 126(10); 138(9); 150(10); 162(10); 174(10); 186(10); 198(9); 200(10); 212(10); 224(10); 236(10); 248(9); 260(10); 272(10);
3	10(9); 22(8); 30(8); 34(9); 42(9); 46(9); 54(9); 58(8); 66(8); 70(9); 78(9); 82(9); 90(9); 94(8); 102(8); 106(9); 114(9); 118(9); 126(9); 130(8); 138(8); 142(9); 150(9); 154(9); 162(9); 166(8); 174(8); 178(9); 186(9); 190(9); 198(9); 202(8); 210(8); 214(9); 222(9); 226(9); 234(9); 238(8); 246(8); 250(9); 258(9); 262(9); 270(9); 274(8);
4	100(9); 112(10); 124(20); 136(19); 148(20); 160(19); 172(20); 184(20); 196(19); 208(20); 220(19); 232(20); 244(20); 256(19); 268(20);
5	24(8); 36(9); 48(9); 60(8); 72(9); 84(9); 88(8); 96(8); 100(9); 108(9); 112(16); 120(9); 124(16); 132(8); 136(17); 144(9); 148(16); 156(9); 160(16); 168(8); 172(17); 180(9); 184(16); 192(9); 196(16); 204(8); 208(17); 216(9); 220(16); 228(9); 232(16); 240(8); 244(17); 252(9); 256(16); 264(9); 268(16); 276(8);

Table A.2

Base Case Pick Up Schedule: Rail Model

Source	Sink 2
6	59(8); 71(16); 83(18); 95(16); 107(17); 119(17); 131(17); 143(16); 155(18); 167(16); 179(17); 191(17); 203(17); 215(17); 227(17); 239(16); 251(17); 263(17); 275(17);
7	99(9); 111(10); 123(20); 135(19); 147(20); 159(19); 171(20); 183(20); 195(19); 207(20); 219(19); 231(20); 243(20); 255(19); 267(20);
8	111(9); 123(10); 135(10); 147(10); 159(10); 171(9); 183(10); 195(10); 207(10); 219(9); 231(10); 243(10); 255(10); 267(10);

Table A.3

Base Case Pick Up Schedule: Rail Model

Source	Sink: 2	Sink: 5
9	115(9); 127(10); 139(10); 150(10); 151(10); 162(9); 163(10); 174(10); 175(10); 186(9); 187(10); 198(10); 199(10); 210(10); 211(9);	222(10); 223(10); 234(10); 235(10); 246(9); 247(10); 258(10); 259(10); 270(10); 271(9);
10	65(8); 77(16); 89(16); 101(16); 113(16); 125(16); 137(16); 149(16); 161(16); 173(16); 185(16); 197(16); 209(16);	221(16); 233(16); 245(16); 257(16); 269(16);
11	3(9); 15(9); 27(8); 39(9); 51(9); 63(8); 75(9); 87(9); 99(8); 111(9); 123(9); 135(8); 147(9); 159(9); 171(8); 183(9); 195(9); 207(8);	219(9); 231(9); 243(8); 255(9); 267(9); 279(8);

Table A.4

Base Case Pick Up Schedule: Rail Model

Source	Sink 2	Sink 4
12	7(9); 19(9); 31(8); 43(9); 55(9); 67(8); 79(9) 91(9); 103(8);	115(9); 127(9); 139(8); 151(9); 163(9); 175(8); 187(9); 199(9); 211(8); 223(9); 235(9); 247(8); 259(9); 271(9);

Table A.5

Base Case Pick Up Schedule: Rail Model

	Sink
Source	3
15	1(9); 5(9); 13(9); 17(9); 25(8); 27(9); 29(8); 37(9); 40(9); 41(9); 49(9); 53(17); 61(8); 65(8); 66(9); 73(9); 77(9); 79(9); 85(9); 89(9); 92(8); 97(8); 101(8); 105(9); 109(9); 113(9); 118(9); 121(9); 125(9); 131(8); 133(8); 137(8); 144(9); 145(9); 149(9); 157(17); 161(9); 169(8); 170(8); 173(8); 181(9); 183(9); 185(9); 193(9); 196(9); 197(9); 205(8); 209(16); 217(9); 221(9); 222(9); 229(9); 233(9); 235(9); 241(8); 245(8); 248(8); 253(9); 257(9); 261(9); 265(9); 269(9); 274(9);

Table A.6

Base Case Pick Up Schedule: Truck Model

Source	Sink 1
1	5(52); 19(52); 33(52); 47(52); 61(52); 75(52); 88(52); 103(52); 117(52); 131(52); 145(52); 159(52); 173(52); 186(52); 201(52); 215(52); 229(52); 243(52); 257(52); 271(52);
2	82(68); 102(69); 114(68); 126(69); 138(68); 150(69); 162(68); 174(69); 186(68); 198(69); 200(68); 212(69); 224(68); 236(69); 248(68); 260(69); 272(68);
3	10(60); 22(56); 30(56); 34(61); 42(61); 46(60); 54(60); 58(56); 66(56); 70(61); 78(61); 82(60); 90(60); 94(56); 102(56); 106(61); 114(61); 118(60); 126(60); 130(56); 138(56); 142(61); 150(61); 154(60); 162(60); 166(56); 174(56); 178(61); 186(61); 190(60); 198(60); 202(56); 210(56); 214(61); 222(61); 226(60); 234(60); 238(56); 246(56); 250(61); 258(61); 262(60); 270(60); 274(56);
4	100(69); 112(68); 124(138); 136(136); 148(138); 160(136); 172(138); 184(136); 196(138); 208(136); 220(138); 232(136); 244(138); 256(136); 268(138);
5	24(56); 36(61); 48(60); 60(56); 72(61); 84(60); 88(56); 96(56); 100(61); 108(61); 112(116); 120(60); 124(117); 132(56); 136(121); 144(61); 148(116); 156(60); 160(117); 168(56); 172(121); 180(617); 184(116); 192(60); 196(117); 204(56); 208(121); 216(61); 220(116); 228(60); 232(117); 240(56); 244(121); 252(61); 256(116); 264(60); 268(117); 276(56);

Table A.7

Base Case Pick Up Schedule: Truck Model

	Sink
Source	2
6	59(56); 71(117); 83(121); 95(116); 107(117); 119(121); 131(116); 143(117); 155(121); 167(116); 179(117); 191(121); 203(121); 215(117); 227(121); 239(116); 251(117); 263(121); 275(116);
7	99(69); 111(68); 123(138); 135(136); 147(138); 159(136); 171(138); 183(136); 195(138); 207(136); 219(138); 231(136); 243(138); 255(136); 267(138);
8	111(69); 123(68); 135(69); 147(68); 159(69); 171(68); 183(69); 195(68); 207(69); 219(68); 231(69); 243(68); 255(69); 267(68);

Table A.8

Base Case Pick Up Schedule: Truck Model

Source	Sink 2	Sink 5
9	115(69); 127(68); 139(69); 150(69); 151(68); 162(68); 163(69); 174(69); 175(68); 186(68); 187(69); 198(69); 199(68); 210(68); 211(69);	222(69); 223(68); 234(68); 235(69); 246(69); 247(68); 258(68); 259(69); 270(69); 271(68);
10	65(56); 77(113); 89(112); 101(112); 113(112); 125(112); 137(112); 149(112); 161(112); 173(112); 185(112); 197(112); 209(112);	221(112); 233(112); 245(112); 257(112); 269(112);
11	3(61); 15(60); 27(56); 39(61); 51(60); 63(56); 75(61); 87(60); 99(56); 111(61); 123(60); 135(56); 147(61); 159(60); 171(56); 183(61); 195(60); 207(56);	219(61); 231(60); 243(56); 255(61); 267(60); 279(56);

Table A.9

Base Case Pick Up Schedule: Truck Model

	Sink	
Source	2	4
12	7(61); 19(60); 31(56); 43(61); 55(60); 67(56); 79(61); 91(60); 103(56);	115(61); 127(60); 139(56); 151(61); 163(60); 175(56); 187(61); 199(60); 211(56); 223(61); 235(60); 247(56); 259(61); 271(60);

Table A.10

Base Case Pick Up Schedule: Truck Model

Source	Sink 3	Sink 4
13	58(69); 64(69); 70(68); 76(68); 82(69); 88(69); 94(68); 100(68); 106(69);	112(69); 118(68); 124(68); 130(69); 136(69); 142(68); 148(68); 154(69); 160(69); 166(68); 172(68); 178(69); 184(69); 190(68); 196(68); 202(69); 208(69); 214(68); 220(68); 226(69); 232(69); 238(68); 244(68); 250(69); 256(69); 262(68); 268(68); 274(69);
14	60(48); 67(48); 71(48); 78(48); 83(48); 90(48); 95(48); 102(48); 107(48);	114(48); 119(48); 126(48); 131(48); 138(48); 143(48); 150(48); 155(48); 162(48); 166(48); 167(48); 174(48); 179(48); 171(48); 178(48); 183(48); 190(48); 195(48); 202(48); 207(48); 214(48); 219(48); 226(48); 231(48); 238(48); 243(48); 250(48); 255(48); 262(48);

Table A.11

Base Case Pick Up Schedule: Truck Model

	Sink
Source	3
15	1(61); 5(61); 13(60); 17(60); 25(56); 27(60); 29(56); 37(61); 40(61); 41(61); 49(60); 53(116); 61(56); 65(56); 66(60); 73(61); 77(61); 79(61); 85(60); 89(60); 92(56); 97(56); 101(56); 105(60); 109(61); 113(61); 118(61); 121(60); 125(60); 131(56); 133(56); 137(56); 144(60); 145(61); 149(61); 157(121); 161(60); 169(56); 170(56); 173(56); 181(61); 183(60); 185(61); 193(60); 196(61); 197(60); 205(56); 209(112)1 217(61); 221(61); 222(60); 229(60); 233(60); 235(61); 241(56); 245(56); 248(56); 253(61); 257(61); 261(60); 265(60); 269(60); 274(61); 277(56);

APPENDIX B

Computer Codes

The five computer codes employed in the study are presented in this Appendix B. Complete documentation is included with each:

CODE I. GENERATION OF INPUT DATA

CODE II. MPS X III SOLUTION PROCEDURE

CODE III. CASK SCHEDULE DETERMINATION ALLOCATION MODEL

CODE IV. MINIMIZATION OF IDLE TIME ITERATIVE SEARCH TECHNIQUE

CODE V. ECONOMIC COMPARISON

Figure 5.1 illustrates how each code is used in the solution of the formulated reference case.

```
/***************************************************************
*                                                              *
*                                                              *
*              GENERATION OF INPUT DATA                        *
*                                                              *
*                                                              *
*   THIS PL1 PROGRAM WRITES INPUT DATA IN REQUIRED             *
*   FORMAT FOR USE BY THE MATHEMATICAL PROGRAMMING SYSTEM      *
*   EXTENDED III (MPSX III) ONTO TAPE.  A FILE CONTAINING      *
*   EACH ROW NAME AND ITS CORRESPONDING RIGHT HAND SIDE        *
*   VALUE IS REQUIRED INPUT.  THE CONSTRAINT MATRIX, AS        *
*   ORIGINALLY FORMULATED BY DANTZIG AND FULKERSON, IS         *
*   THAT OF A TRANSPORTATION PROBLEM WITH ADDITIONAL           *
*   CONSTRAINTS.                                               *
*                                                              *
***************************************************************/
THESIS:PROCEDURE OPTIONS(MAIN);
DCL 1 OUTREC,
    2 JUNK1  CHAR(4) INITIAL('    '),
    2 ROW1   CHAR(4),
    2 ROW2   CHAR(4),
    2 JUNK2  CHAR(2) INITIAL('  '),
    2 ROW3   CHAR(4),
    2 JUNK3  CHAR(6) INITIAL((6)' '),
    2 CONS1  CHAR(3) INITIAL('1. '),
    2 JUNK4  CHAR(12) INITIAL((12)' '),
    2 ROW4   CHAR(4),
    2 JUNK5  CHAR(6) INITIAL((6)' '),
    2 CONS2  CHAR(3) INITIAL('1. '),
    2 JUNK6  CHAR(28) INITIAL((28)' ');
DCL COL1 CHAR(8) BASED(P);
P=ADDR(ROW1);
DCL A(411) CHAR(4), B(410) CHAR(4), BEXCP(410) FIXED BINARY
    INITIAL((410)0),(NAMED,CONST)CHAR(4),(JX,NEXCEP) FIXED
    BINARY, (ARHS(411),BRHS(410)) CHAR(3);
DCL  (INEXP,ANAMES,BNAMES) STREAM;
DCL(RANAMES,RBNAMES) STREAM;
DCL OUTPUT FILE RECORD, SEQL;
DCL OUTLINE CHAR(80);
DCL 1 COLZ,
    3 Z      CHAR(1) INITIAL('Z'),
    3 ZCOL   CHAR(4),
    3 ZJUNK  CHAR(3) INITIAL('   ');
/***************************************************************
*                                                              *
* READ IN THE VARIABLES IN THE LOWER DIAGONAL PORTION OF       *
* THE CONSTRAINT MATRIX WHICH ARE CONSTRAINED TO BE ZERO       *
*                                                              *
***************************************************************/
ON ENDFILE (INEXP) GO TO DONE1;
   DO WHILE ('1'B);
```

```
        GET FILE(INEXP) EDIT(JX,NEXCP)
             (COL(19),F(3),COL(29),F(1));
        BEXCP(JX)=NEXCP;
        END;
DONE1: ;
/************************************************************
*                                                           *
* READ IN THE ROW NAMES CORRESPONDING TO ALPHA VARIABLES    *
* (ARRIVAL TIMES) AND THEIR RIGHT HAND SIDE VALUES FOR      *
* THE TRUCK MODEL.                                          *
*                                                           *
************************************************************/
ON ENDFILE ( ANAMES) GO TO DONE2;
   I=0;
   DO WHILE ('1'B);
        GET FILE(ANAMES) EDIT (NAMED,CONST)
             (COL(18),A(4),COL(29),A(3));
        I=I+1;
        A(I)=NAMED;
        ARHS(I)=CONST;
        END;
DONE2: ;
/************************************************************
*                                                           *
* READ IN THE ROW NAMES CORRESPONDING TO BETA VARIABLES     *
* (DELIVERY TIMES) AND THEIR RIGHT HAND SIDE VALUES FOR     *
* THE TRUCK MODEL.                                          *
*                                                           *
************************************************************/
   ON ENDFILE(BNAMES) GO TO DONE3;
   I=0;
   DO WHILE ('1'B);
        GET FILE(BNAMES) EDIT(NAMED,CONST)
             (COL(18),A(4),COL(29),A(3));
        I=I+1;
        B(I)=NAMED;
        BRHS(I)=CONST;
        END;
DONE3: OPEN FILE(OUTPUT) OUTPUT;
/************************************************************
*                                                           *
* WRITE THE DATA IN THE FORM REQUIRED FOR USE BY THE        *
* MATHEMATICAL PROGRAMMING SYSTEM EXTENDED III.             *
*                                                           *
************************************************************/
        OUTLINE='NAME          PROJECT';
        WRITE FILE(OUTPUT) FROM (OUTLINE);
```

```
/*************************************************************
*                                                            *
* FIRST, WRITE THE OBJECTIVE  FUNCTION NAME (OBJ), THE       *
* ROW NAMES, AND INDICATE THE TYPE OF CONSTRAINTS.           *
*                                                            *
*************************************************************/
       OUTLINE='ROWS';
       WRITE FILE(OUTPUT) FROM (OUTLINE);
       OUTLINE=' N  OBJ';
       WRITE FILE(OUTPUT) FROM (OUTLINE);
       DO I=1 TO 411;
            OUTLINE=' E   ' || A(I);
            WRITE FILE (OUTPUT) FROM (OUTLINE);
            END;
       DO I=1 TO 410;
            OUTLINE=' E   ' || B(I);
            WRITE FILE(OUTPUT) FROM (OUTLINE);
            END;
/*************************************************************
*                                                            *
* WRITE THE COLUMN NAMES AND LIST ALL ROW INTERSECTIONS      *
* AND COEFFICIENTS.                                          *
*                                                            *
*************************************************************/
            OUTLINE='COLUMNS';
       WRITE FILE (OUTPUT) FROM (OUTLINE);
BCNT:  DO I=1 TO 410;
ACNT:  DO J=I+(1+BEXCP(I)) TO 411;
       ROW1,ROW3=A(J);
       ROW2,ROW4=B(I);
       WRITE FILE (OUTPUT) FROM (OUTREC);
       END ACNT;
       END BCNT;
   DO I=1 TO 411;
       ZCOL=A(I);
       COL1=COLZ.Z||COLZ.ZCOL||COLZ.ZJUNK;
       ROW3=A(I);
       ROW4='OBJ ';
       WRITE FILE(OUTPUT) FROM (OUTREC);
       END;
ROW4='     ';
CONS2='    ';
   DO I=1 TO 410;
       ZCOL=B(I);
       COL1=COLZ.Z||COLZ.ZCOL||COLZ.ZJUNK;
       ROW3=B(I);
       WRITE FILE(OUTPUT) FROM (OUTREC);
       END;
       END;
```

```
/**************************************************************
*                                                             *
* WRITE THE RIGHT HAND SIDE VALUE FOR EACH CONSTRAINT.        *
*                                                             *
**************************************************************/
   OUTLINE='RHS';
   WRITE FILE(OUTPUT) FROM (OUTLINE);
       COL1='RHS     ';
       DO I=1 TO 411 ;
       ROW3=A(I);
       CONS1=ARHS(I);
       WRITE FILE(OUTPUT) FROM(OUTREC);
       END;
       DO I=1 TO 410;
       ROW3= B(I);
       CONS1=BRHS(I);
       WRITE FILE(OUTPUT) FROM (OUTREC);
       END;
   OUTLINE='ENDATA';
   WRITE FILE(OUTPUT) FROM (OUTLINE);
/**************************************************************
*                                                             *
*  INPUT AN INITIAL BASIC SOLUTION TO BE USED BY THE          *
*  MPSX III PROGRAM.                                          *
*                                                             *
**************************************************************/
       OUTLINE='NAME          INITSOL';
       WRITE FILE(OUTPUT) FROM (OUTLINE);
       JUNK1=' XL ';
       ROW3='    ';
       DO I=1 TO 411;
       ZCOL=A(I);
       COL1=COLZ.Z||COLZ.ZCOL||COLZ.ZJUNK;
       CONS1=ARHS(I);
       WRITE FILE(OUTPUT) FROM (OUTREC);
            END;
       DO I=1 TO 410;
       ZCOL=B(I);
       COL1=COLZ.Z||COLZ.ZCOL||COLZ.ZJUNK;
       CONS1=BRHS(I);
       WRITE FILE(OUTPUT) FROM (OUTREC);
            END;
   OUTLINE='ENDATA';
       WRITE FILE(OUTPUT) FROM (OUTLINE);
/**************************************************************
*                                                             *
* INPUT THE NEW RIGHT HAND SIDE FOR THE RAIL MODEL.           *
* THIS DATA WILL BE USED BY THE REVISE STATEMENT IN           *
* THE MPSX III PROGRAM.                                       *
*                                                             *
**************************************************************/
```

```
        OUTLINE='NAME            CHRHS3';
    WRITE FILE(OUTPUT) FROM (OUTLINE);
    OUTLINE='RHS';
    WRITE FILE(OUTPUT) FROM (OUTLINE);
    OUTLINE='  MODIFY';
    WRITE FILE(OUTPUT) FROM (OUTLINE);
JUNK1='    ';
ROW1='RHS ';
ROW2='    ';
CONS2='   ';
ROW4='    ';
ON ENDFILE (RANAMES) GO TO DONE4;
    I=0;
    DO WHILE ('1'B);
        GET FILE(RANAMES) EDIT(NAMED,CONST)
              (COL(18),A(4),COL(29),A(3));
        I=I+1;
        A(I)=NAMED;
        ARHS(I)=CONST;
        END;
DONE4: ;
    ON ENDFILE(RBNAMES) GO TO DONE5;
    I=0;
    DO WHILE ('1'B);
        GET FILE(RBNAMES) EDIT(NAMED,CONST)
              (COL(18),A(4),COL(29),A(3));
        I=I+1;
        B(I)=NAMED;
        BRHS(I)=CONST;
        END;
DONE5: ;
        DO I=1 TO 411 ;
        ROW3=A(I);
        CONS1=ARHS(I);
        WRITE FILE(OUTPUT) FROM(OUTREC);
        END;
        DO I=1 TO 410;
        ROW3= B(I);
        CONS1=BRHS(I);
        WRITE FILE(OUTPUT) FROM (OUTREC);
        END;
    OUTLINE='ENDATA';
    WRITE FILE(OUTPUT) FROM (OUTLINE);
    STOP;
    END THESIS;
```

```
*****************************************************************
*                                                               *
*                                                               *
*              MPSX III SOLUTION PROCEDURE                      *
*                                                               *
*                                                               *
* THIS PROGRAM SOLVES TWO LINEAR PROGRAMMING PROBLEMS.          *
* THE SECOND PROBLEM IS IDENTICAL TO THE FIRST EXCEPT           *
* FOR A MODIFIED RIGHT HAND SIDE.  INPUT DATA WAS               *
* GENERATED BY A PL/1 PROGRAM AND WRITTEN ON TAPE.              *
*                                                               *
*                                                               *
*****************************************************************
         PROGRAM
*****************************************************************
*                                                               *
*     ESTABLISH INITIAL SETTINGS FOR TOLERANCE,                 *
*     FREQUENCIES, AND DEMANDS BY DEFAULT.                      *
*                                                               *
*****************************************************************
         INITIALZ
*****************************************************************
*                                                               *
*     INTRODUCE NAME OF INPUT DATA,OBJECTIVE FUNCTION,          *
*     AND RIGHT HAND SIDE.  SPECIFY IN COMMUNICATIONS           *
*     REGION.                                                   *
*                                                               *
*****************************************************************
         MOVE(XDATA,'PROJECT')
         MOVE(XPBNAME,'BETHEL')
         MOVE(XOBJ,'OBJ')
         MOVE(XRHS,'RHS')
*****************************************************************
*                                                               *
*     SET OP WORK FILE TO SOLVE PROBLEM.                        *
*                                                               *
*****************************************************************
         SETUP('MIN')
*****************************************************************
*                                                               *
*     PLACE INPUT DATA ON PROBFILE.                             *
*                                                               *
*****************************************************************
         CONVERT
```

```
*****************************************************************
*                                                               *
*     CALL MAIN OPTIMIZATION PROCEDURE, VARIFORM.               *
*     VARIFORM OPTIMIZES THE PROBLEM USING A PRIMAL             *
*     ALGORITHM.  EXITS WITH AN INTERNALLY-STORED               *
*     FEASIBLE, OPTIMAL BASIS.                                  *
*                                                               *
*****************************************************************
        VARIFORM
*****************************************************************
*                                                               *
*     STORE THE OPTIMAL BASIS ON TAPE FOR FUTURE                *
*     REFERENCE.                                                *
*                                                               *
*****************************************************************
        PRESERVE('NAME',CASE)
*****************************************************************
*                                                               *
*     PRINT THE OPTIMAL BASIS.                                  *
*                                                               *
*****************************************************************
        SOLUTION('BASIS')
*****************************************************************
*                                                               *
*     INTRODUCE NEW PROBLEM NAME FOR THE RAIL MODEL AND         *
*     THE NEW RIGHT HAND SIDE.                                  *
*                                                               *
*****************************************************************
        MOVE(XOLDNAME,'BETHEL')
        MOVE(XPBNAME,'BETHELR')
        MOVE(XDATA,'CHRHS3')
*****************************************************************
*                                                               *
*     REVISE THE ORIGINAL MODEL RIGHT HAND SIDE                 *
*     ACCORDING TO THE INPUT DATA CHRHS3.                       *
*                                                               *
*****************************************************************
        REVISE
*****************************************************************
*                                                               *
*     SETUP THE NEW PROBLEM.                                    *
*                                                               *
*****************************************************************
        SETUP
*****************************************************************
*                                                               *
*     RESET THE OPTIMAL BASIS OF THE FIRST PROBLEM.             *
*                                                               *
*****************************************************************
        RESET('NAME',CASE)
        MOVE(CASE,'BETHELR2')
```

```
**************************************************************
*                                                            *
*     SOLVE THE MODIFIED PROBLEM USING THE OPTIMAL           *
*     SOLUTION OF THE PREVIOUS FORMULATION AS AN             *
*     INITIAL SOLUTION.                                      *
*                                                            *
**************************************************************
        VARIFORM
**************************************************************
*                                                            *
*     STORE THE OPTIMAL BASIS ON TAPE FOR FUTURE             *
*     REFERENCE.                                             *
*                                                            *
**************************************************************
        PRESERVE('NAME',CASE)
**************************************************************
*                                                            *
*     PRINT THE OPTIMAL BASIS OF THE RAIL MODEL.             *
*                                                            *
**************************************************************
        SOLUTION('BASIS')
        EXIT
        PEND
```

```
C*************************************************************
C                                                            *
C                                                            *
C               CASK SCHEDULE DETERMINATION                  *
C                    ALLOCATION MODEL                        *
C                                                            *
C                                                            *
C THIS FORTRAN PROGRAM DETERMINES A FEASIBLE UTILIZATION     *
C PLAN FOR SPENT FUEL CASKS.  THE INDICATED SCHEDULE IS      *
C OBTAINED FROM THE OPTIMAL SOLUTION OF THE DANTZIG-         *
C FULKERSON MODEL.  THREE SETS OF INPUT DATA ARE REQUIRED;   *
C                                                            *
C      (1) THE A MATRIX:  FOR EACH ALPHA VARIABLE,           *
C          THIS MATRIX CONTAINS THE CORRESPONDING            *
C          PICKUP TIME, PICKUP POINT, DELIVERY POINT,        *
C          AND BETA VARIABLE REPRESENTING ARRIVAL            *
C          TIME AT THE DELIVERY POINT.                       *
C                                                            *
C      (2) THE B MATRIX:  THIS MATRIX CONTAINS               *
C          EACH BASIC VARIABLE AND ITS VALUE AS              *
C          OBTAINED FROM THE MPS SOLUTION.  ALL              *
C          NONBASIC VARIABLES EQUAL ZERO.                    *
C                                                            *
C      (3) THE SA ARRAY:  THIS ARRAY CONTAINS                *
C          THE SLACK VARIABLES CORRESPONDING TO              *
C          CASK START TIMES.  THOSE SLACKS WHICH             *
C          ARE NONBASIC ARE ASSIGNED ZERO VALUES.            *
C                                                            *
C*************************************************************
      INTEGER A(411,4), B(411,410), SA(411), T(411,3)
C*************************************************************
C                                                            *
C         READ IN THE A MATRIX                               *
C                                                            *
C*************************************************************
      DO 10 J1=1,411
      READ (5,*) I1,I2,I3,I4
      A(J1,1)=I1
      A(J1,2)=I2
      A(J1,3)=I3
 10   A(J1,4)=I4
C*************************************************************
C                                                            *
C      INITIALIZE B MATRIX AND SA ARRAY TO ZERO              *
C                                                            *
C*************************************************************
      DO 20 J2=1,411
      SA(J2)=0
      DO 20 J3 =1,410
 20   B(J2,J3)=0
```

```
C****************************************************************
C                                                               *
C        INPUT NON-ZERO ELEMENTS OF B AND SA                    *
C        FIRST, READ IN ELEMENTS OF SA                          *
C                                                               *
C****************************************************************
      READ (5,*) N1
      DO 30 J3=1,N1
      READ (5,*) I5,J4
 30   SA(I5)=J4
C****************************************************************
C                                                               *
C       NOW READ IN NON-ZERO ELEMENTS OF B                      *
C                                                               *
C****************************************************************
      READ (5,*) N2
      DO 40 J5=1,N2
      READ(5,*,END=41)I6,I7,I8
 40   B(I6,I7)=I8
      GO TO 45
 41   WRITE (6,*) I6,I7,I8,J5
C****************************************************************
C                                                               *
C         INITIALIZE THE NUMBER OF REQUIRED CASKS TO ZERO       *
C                                                               *
C****************************************************************
 45   K1=0
      K=0
 50   K=K+1
C****************************************************************
C                                                               *
C        CHECK IF ALL PICKUP TIMES HAVE BEEN                    *
C        INCORPORATED INTO THE SCHEDULES.                       *
C                                                               *
C****************************************************************
      IF(K.GT.411) GO TO 95
C****************************************************************
C                                                               *
C       CHECK EACH SLACK FOR THE NUMBER OF CASKS                *
C       BEGINNING THEIR SCHEDULES.                              *
C                                                               *
C****************************************************************
 60   IF(SA(K).EQ.0) GO TO 50
      IF(K1 .EQ. 0)  WRITE (6,100)
      IF(K1 .EQ. 0)  GO TO 63
  100 FORMAT ('1'/////////,T33,'FEASIBLE RAIL SCHEDULE'/
     * T33,'DANTZIG-FULKERSON MODEL'//)
      INT=L/5
      WRITE (6,300) K1,((T(L1,L2),L2=1,3),L1=1,L)
  300 FORMAT('-',T16,60('*'),
     * //T16,'SCHEDULE FOR CASK NO. ',I4//
```

```
     *(T16,5('T(',I2,',',I1,')=',I3,';')))
   63 CONTINUE
C*****************************************************************
C                                                                *
C INITIALIZE THE NUMBER OF TRIPS PER CASK K1 TO ZERO             *
C                                                                *
C*****************************************************************
      L=0
C*****************************************************************
C                                                                *
C      INITIALIZE THE T MATRIX TO ZERO.                          *
C      THE T MATRIX STORES THE SCHEDULE OF CASK K1               *
C      BEFORE THE SCHEDULE IS PRINTED.                           *
C                                                                *
C*****************************************************************
      DO 65 JO=1,411
      DO 65 NO=1,3
 65   T(JO,NO)=0
      K1=K1+1
C*****************************************************************
C                                                                *
C      DECREMENT THE NUMBER OF CASKS BY ONE                      *
C                                                                *
C*****************************************************************
      SA(K)=SA(K)-1
      I=K
 70   L=L+1
C*****************************************************************
C                                                                *
C      STORE SCHEDULE INFORMATION FOR TRIP L OF CASK K1.         *
C      T(L,1) CONTAINS THE PICKUP POINT REFERENCE NO.            *
C      T(L,2) CONTAINS THE DELIVERY POINT REFERENCE NO.          *
C      T(L,3) CONTAINS THE PICKUP TIME REFERENCE NO.             *
C      IB IS THE CORRESPONDING B VARIABLE WHICH                  *
C      DESIGNATES ARRIVAL TIME AT THE DELIVERY POINT.            *
C                                                                *
C*****************************************************************
      T(L,1)=A(I,2)
      T(L,2)=A(I,3)
      T(L,3)=A(I,1)
      IB=A(I,4)
      GO TO 78
 75   IB=IB+1
      IF(IB.EQ.411) GO TO 60
C*****************************************************************
C                                                                *
C   FOR THE INDICATED B VALUE, FIND THE NEXT A ASSIGNMENT        *
C                                                                *
C*****************************************************************
 78   DO 90 J=1,411
      IF((B(J,IB).EQ.0).OR.(A(J,1).LE.T(L,3))) GO TO 80
```

```
      B(J,IB)=B(J,IB)-1
      I=J
      GO TO 70
80    IF(J.EQ.411) GO TO 75
90    CONTINUE
95    WRITE (6,100) K1,((T(L1,L2),L2=1,3),L1=1,L)
      STOP
      END
```

```
C*****************************************************************
C                                                                *
C                                                                *
C               MINIMIZATION OF IDLE TIME                        *
C               ITERATIVE SEARCH TECHNIQUE                       *
C                                                                *
C                                                                *
C       THIS PROGRAM DETERMINES FEASIBLE CASK UTIL-              *
C       IZATION SCHEDULES IN WHICH CASK IDLE TIME IS             *
C       MINIMIZED.  THE TOTAL NUMBER OF CASKS TO BE              *
C       EMPLOYED IN THE PLANNING HORIZON MUST BE SUPPLIED.       *
C       THE USER MUST ALSO INPUT AN A MATRIX WHICH               *
C       CONTAINS EACH PICKUP POINT, DELIVERY POINT,              *
C       PICKUP TIME, AND THE NUMBER OF CASKS REQUIRED            *
C       FOR EACH TRANSPORT LOAD.                                 *
C       IN ADDITION TO DETERMINING A SCHEDULE WHICH              *
C       MINIMIZES IDLE TIME, THE PROGRAM TABULATES THE           *
C       TOTAL NUMBER OF MILES TRAVELED EACH YEAR IN              *
C       THE PLANNING HORIZON, THE NUMBER OF CASKS IN USE         *
C       EACH YEAR, AND THE TOTAL NUMBER OF TRIPS EACH YEAR.      *
C       TO ACCOMPLISH THIS, A MILEAGE CHART (MATRIX M) MUST      *
C       BE INPUT.                                                *
C                                                                *
C*****************************************************************
      INTEGER*2 M(15,5),A(411,4),T(279,3)
      INTEGER S(23,3)
      DO 1 J0=1,23
C*****************************************************************
C                                                                *
C       INITIALIZE THE S MATRIX TO ZERO.  THE S MATRIX           *
C       CONTAINS THE NUMBER OF CASKS IN USE EACH YEAR IN         *
C       ITS FIRST COLUMN, THE CUMULATIVE NUMBER OF MILES         *
C       TRAVELED EACH YEAR IN ITS SECOND COLUMN, AND THE         *
C       NUMBER OF TRIPS EACH YEAR IN ITS THIRD COLUMN.           *
C                                                                *
C*****************************************************************
      DO 1 K0=1,3
 1    S(J0,K0)=0
C*****************************************************************
C                                                                *
C       INPUT THE MILEAGE CHART, MATRIX M                        *
C                                                                *
C*****************************************************************
      READ,((M(J1,K1),K1=1,5),J1=1,15)
      DO 3 J2=1,411
C*****************************************************************
C                                                                *
C       READ IN THE A MATRIX                                     *
C                                                                *
C*****************************************************************
      READ, I1,I2,I3
```

```
      A(J2,1)=I1
      A(J2,2)=I2
 3    A(J2,3)=I3
      DO 4 J3=1,411
      READ,I4
 4    A(J3,4)=I4
C***********************************************************************
C                                                                      *
C       READ THE NUMBER OF CASKS TO BE USED                            *
C                                                                      *
C***********************************************************************
      READ,NC
C***********************************************************************
C                                                                      *
C       DETERMINE A SCHEDULE FOR EACH CASK K                           *
C                                                                      *
C***********************************************************************
      DO 15 K=1,NC
C***********************************************************************
C                                                                      *
C       INITIALIZE THE T MATRIX TO ZERO.  THE T MATRIX                 *
C       STORES THE SCHEDULE OF CASK K BEFORE IT IS PRINTED.            *
C                                                                      *
C***********************************************************************
      DO 5 J4=1,279
      DO 5 K4=1,3
 5    T(J4,K4)=0
C***********************************************************************
C                                                                      *
C       INITIALIZE THE FIRST POSSIBLE PICKUP TIME TO 1 AND             *
C       THE NUMBER OF TRIPS PER CASK K TO ZERO.                        *
C                                                                      *
C***********************************************************************
      L1=1
      L=0
 6    IF(L1.GT.279) GO TO 12
 7    DO 11 J=1,411
C***********************************************************************
C                                                                      *
C       IF CASK 1 IS IDLE AT TIME L1 AND A POSITIVE NUMBER             *
C       OF TRIPS REMAIN AT TIME L1, ADD TRIP TO SCHEDULE               *
C                                                                      *
C***********************************************************************
 8    IF(A(J,1) .EQ. L1 .AND. A(J,4) .GT. 0) GO TO 10
      IF(A(J,1) .GT. L1) GO TO 9
      GO TO 11
 9    L1=L1+1
      GO TO 8
```

```
C*****************************************************************
C                                                                *
C       TRIP ADDED TO SCHEDULE.  INCREMENT THE NUMBER OF         *
C       TRIPS AND THE NEXT FEASIBLE SCHEDULE TIME.               *
C                                                                *
C*****************************************************************
 10   L=L+1
      L1=L1+1
      T(L,1)=A(J,2)
      T(L,2)=A(J,3)
      T(L,3)=A(J,1)
      A(J,4)=A(J,4)-1
 11   CONTINUE
      L1=L1+1
C*****************************************************************
C                                                                *
C       CHECK IF SCHEDULE IS COMPLETE                            *
C                                                                *
C*****************************************************************
      GO TO 6
 12   K1=12
C*****************************************************************
C                                                                *
C       FOR THE COMPLETED SCHEDULE, UPDATE THE NUMBER OF         *
C       CASKS IN USE EACH YEAR.                                  *
C                                                                *
C*****************************************************************
      DO 13 N=1,23
C*****************************************************************
C                                                                *
C       FOR THE STARTUP YEAR OF CASK K AND EACH SUBSEQUENT       *
C       YEAR OF THE PLANNING HORIZON, INCREMENT THE NUMBER       *
C       OF CASKS IN USE BY ONE.                                  *
C                                                                *
C*****************************************************************
      IF(T(1,3).GT.K1) GO TO 13
      S(N,1)=S(N,1)+1
C*****************************************************************
C                                                                *
C       FOR THE TERMINATION YEAR OF CASK K AND EACH              *
C       SUBSEQUENT YEAR OF THE PLANNING  HORIZON,                *
C       DECREMENT THE NUMBER OF CASKS IN USE BY ONE.             *
C                                                                *
C*****************************************************************
      IF(T(L,3) .GT. K1) GO TO 13
      S(N,1)=S(N,1) - 1
 13   K1=K1 + 12
```

```
C***********************************************************************
C                                                                      *
C       DETERMINE THE CUMULATIVE NUMBER OF TRIPS                       *
C       AND MILES TRANSPORTED EACH YEAR.                               *
C                                                                      *
C***********************************************************************
      DO 14 J1=1,23
      K2=(J1-1)*12
      DO 14 M2=1,L
C***********************************************************************
C                                                                      *
C       IF THIS IS THE LAST TRIP OF CASK K, ADD THE                    *
C       MILEAGE FROM SOURCE TO SINK.                                   *
C                                                                      *
C***********************************************************************
      IF(M2.EQ.L.AND.T(M2,3).GT.K2.AND.T(M2,3).LT.(K2+13))
     2S(J1,2)=S(J1,2) + M(T(M2,1),T(M2,2))
      IF(M2 .EQ.L) GO TO 14
C***********************************************************************
C                                                                      *
C       FOR THE INITIAL AND INTERMEDIATE TRIPS OF CASK K,              *
C       ADD THE MILEAGE FROM SOURCE TO SINK AND THE MILEAGE            *
C       FROM THAT SINK TO THE NEXT SCHEDULED PICKUP POINT.             *
C                                                                      *
C***********************************************************************
      IF (T(M2,3) .GT.K2 .AND. T(M2,3) .LT. (K2+13))
     *        S(J1,2)=S(J1,2)+M(T(M2,1),T(M2,2))
     *        +M(T(M2+1,1),T(M2,2))
C***********************************************************************
C                                                                      *
C       FOR EACH TRIP  SCHEDULED FOR CASK K, INCREMENT                 *
C       THE NUMBER OF TRIPS PER YEAR BY ONE FOR EACH                   *
C       APPROPRIATE YEAR.                                              *
C                                                                      *
C***********************************************************************
 14   IF (T(M2,3).GT.K2.AND.T(M2,3).LT.(K2+13))
     *    S(J1,3)=S(J1,3)+1
      PRINT 300
      PRINT 100,K
      PRINT 200,((T(L7,L8),L8=1,3),L7=1,L)
 15   CONTINUE
      PRINT 600
      PRINT 700
      DO 16 LXY=1,23
 16   PRINT 500,LXY,S(LXY,1),S(LXY,2)
 100  FORMAT(' ','SCHEDULE FOR CASK NO.',I4)
 200  FORMAT(' ',5('T(',I2,',',I2,')=',I4,';'))
 300  FORMAT(' ',85('*'))
 500  FORMAT(' ',3X,I2,6X,I4,5X,I9)
 600  FORMAT('+',9X,'NO. CASKS',3X,'NO. MILES')
 700  FORMAT(' ',2X,'YEAR',4X,'IN  USE', 4X,'TRAVELED',///)
```

```
STOP
END
```

```
C*************************************************************
C                                                            *
C                                                            *
C                     ECONOMIC COMPARISON                    *
C                                                            *
C                                                            *
C THIS COMPUTER CODE EVALUATES SIX TRANSPORT ALTERNATIVES    *
C FOR IRRADIATED FUEL ASSEMBLIES:                            *
C                                                            *
C      1.  TRUCK TRANSPORT,LEASE CASK                        *
C      2..  TRUCK TRANSPORT,PURCHASE CASK                    *
C      3.  RAIL TRANSPORT,LEASE CASK                         *
C      4.  RAIL TRANSPORT,PURCHASE CASK                      *
C      5.  RAIL TRANSPORT,LEASE CASK,DEDICATED TRAIN         *
C      6.  RAIL TRANSPORT,PURCHASE CASK,DEDICATED TRAIN      *
C                                                            *
C REQUIRED STATISTICS ARE CONTAINED IN THE S MATRIX. THIS    *
C MATRIX HAS ONE ROW FOR EACH YEAR OF THE PLANNING HORIZON   *
C PLUS ONE ADDITIONAL ROW OF ZEROS. S IS INPUT BY COLUMNS    *
C WHERE:                                                     *
C                                                            *
C      COL1-# ADDITIONAL CASKS REQUIRED(TRUCK)               *
C      COL2-# MILES TRAVELED IN YEAR (TRUCK)                 *
C      COL3-# TRIPS IN YEAR (TRUCK)                          *
C      COL4-  DISCOUNT FACTORS                               *
C      COL5-# ADDITIONAL CASKS REQUIRED (RAIL)               *
C      COL6-# MILES TRAVELED IN YEAR (RAIL)                  *
C      COL7-# TRIPS IN YEAR (RAIL)                           *
C                                                            *
C A PRESENT WORTH COST IS OBTAINED. VARIABLE DEFINITIONS     *
C INCLUDE:                                                   *
C                                                            *
C      COSTL  COST TO LEASE CASK PER DAY                     *
C      WT     LOADED CASK WEIGHT                             *
C      CAP    CASK CAPACITY                                  *
C      CMH    COST OF MATERIALS HANDLING                     *
C      NT     NUMBER OF TRIPS DURING PLANNING HORIZON        *
C      COSTP  COST TO PURCHASE CASK                          *
C      SUR    SURCHARGE ASSOCIATED WITH USE OF               *
C             DEDICATED TRAIN                                *
C                                                            *
C                                                            *
C*************************************************************
      DIMENSION S(24,7)
C*************************************************************
C                                                            *
C      READ IN THE S MATRIX                                  *
C                                                            *
C*************************************************************
      READ,((S(L1,L2),L1=1,24),L2=1,7)
```

```
C***************************************************************
C                                                              *
C     THESE STATISTICS CHARACTERIZE THE TRUCK                  *
C     TRANSPORT OPTIONS.                                       *
C                                                              *
C***************************************************************
      COSTL=650.
      WT=25.
      CAP=1.
      CMH=.0178
      NT=29734
      COSTP=500000.
      SUR=0.0
C***************************************************************
C                                                              *
C     N,M, AND L IDENTIFY COLUMNS OF THE S MATRIX WHICH        *
C     CONTAIN TRUCK STATISTICS.                                *
C                                                              *
C***************************************************************
      N=3
      M=1
      L=2
      DO 5 JO=1,3
C***************************************************************
C                                                              *
C     THE FIRST TIME THROUGH THE DO-LOOP, THE TRUCK            *
C     OPTIONS ARE EVALUATED.                                   *
C                                                              *
C***************************************************************
      IF(JO.EQ.1) GO TO 1
C***************************************************************
C                                                              *
C     THE SECOND AND THIRD TIMES THROUGH THE LOOP, RAIL        *
C     OPTIONS ARE EVALUATED.  N,M, AND L MUST BE REDEFINED.*
C                                                              *
C***************************************************************
      M=5
      L=6
      N=7
C***************************************************************
C                                                              *
C     THESE STATISTICS CHARACTERIZE THE RAIL TRANSPORT         *
C     OPTIONS.  THE SECOND TIME THROUGH THE LOOP, THE          *
C     RAIL-REGULAR FREIGHT OPTIONS ARE EVALUATED.              *
C                                                              *
C***************************************************************
      CMH=.0135
      COSTL=3000.
      WT=75.
      NT=4339
      CAP=7.
```

```
      COSTP=1300000.
C*****************************************************************
C                                                                *
C     THE THIRD TIME THROUGH THE LOOP, THE RAIL-DEDICATED        *
C     TRAIN OPTIONS ARE EVALUATED.  THESE ARE THE ONLY           *
C     OPTIONS FOR WHICH A SURCHARGE IS ADDED.                    *
C                                                                *
C*****************************************************************
      IF(J0.EQ.3) SUR=.0241
C*****************************************************************
C                                                                *
C     SUML IS THE COST WHICH RESULTS WHEN THE LEASE              *
C     OPTION IS BEING EMPLOYED.                                  *
C                                                                *
C*****************************************************************
 1    SUML=S(1,N)*COSTL*30.
C*****************************************************************
C                                                                *
C     SUMP IS THE COST WHICH RESULTS WHEN THE PURCHASE           *
C     OPTION IS BEING EMPLOYED.                                  *
C                                                                *
C*****************************************************************
      SUMP=S(1,M)*COSTP
C*****************************************************************
C                                                                *
C     SUMM ACCUMULATES THE TOTAL NUMBER OF MILES TRAVELED        *
C     DURING THE ENTIRE PLANNING HORIZON.                        *
C                                                                *
C*****************************************************************
      SUMM=0
      DO 2 J1=1,23
C*****************************************************************
C                                                                *
C     CCL IS THE COST INCURRED FROM CASK LEASE.                  *
C                                                                *
C*****************************************************************
      CCL=S(J1+1,N) * COSTL*30.
C*****************************************************************
C                                                                *
C     CFM IS THE COST WHICH RESULTS FROM FREIGHT                 *
C     AND MATERIALS HANDLING.                                    *
C                                                                *
C*****************************************************************
      CFM=(.08+CMH+SUR)*S(J1,L)         *WT
C*****************************************************************
C                                                                *
C     CCP IS THE COST INCURRED FROM CASK PURCHASE.               *
C                                                                *
C*****************************************************************
      CCP=S(J1 +1,M) * COSTP
```

```
C*************************************************************
C                                                            *
C     UPDATE THE COST STATISTICS FOR EACH YEAR OF            *
C     THE PLANNING HORIZON.                                  *
C                                                            *
C*************************************************************
      SUML=SUML+(CCL+CFM)*S(J1,4)
      SUMP=SUMP+(CCP+CFM)*S(J1,4)
C*************************************************************
C                                                            *
C     UPDATE THE CUMULATIVE NUMBER OF MILES TRAVELED.        *
C                                                            *
C*************************************************************
 2    SUMM=SUMM+S(J1,L)
C*************************************************************
C                                                            *
C     CONVERT COSTS TO $/ASSEMBLY.                           *
C                                                            *
C*************************************************************
      SUML=SUML/ CAP
      SUMP=SUMP/ CAP
C*************************************************************
C                                                            *
C     CONVERT COSTS TO $/ASSEMBLY MILE.                      *
C                                                            *
C*************************************************************
      SUML1=SUML/SUMM
      SUMP1=SUMP/SUMM
C*************************************************************
C                                                            *
C     PRINT THE RESULTS.                                     *
C                                                            *
C*************************************************************
      IF(JO.EQ.2) GO TO 3
      IF(JO.EQ.3) GO TO 4
      PRINT 200
      PRINT 100, SUMP,SUMP1
      PRINT 300
      PRINT 100,SUML,SUML1
      GO TO 5
 3    PRINT 400
      PRINT 100, SUMP,SUMP1
      PRINT 500
      PRINT 100,SUML,SUML1
      GO TO 5
 4    PRINT 600
      PRINT 100, SUMP,SUMP1
      PRINT 700
      PRINT 100,SUML,SUML1
 5    CONTINUE
 100  FORMAT(1X,7X,'COST=$',F12.2,'  PER ASSEMBLY',//,8X,
```

```
     2F12.5,'  PER ASSEMBLY MILE',////)
200  FORMAT(1X,'TRUCK:PURCHASE OPTION;')
300  FORMAT(1X,'TRUCK:LEASE OPTION;')
400  FORMAT(1X,'RAIL:PURCHASE OPTION;')
500  FORMAT(1X,'RAIL: LEASE OPTION;')
600  FORMAT(1X,'RAIL: PURCHASE OPTION, DEDICATED TRAIN;')
700  FORMAT(1X,'RAIL: LEASE OPTION, DEDICATED TRAIN;')
     STOP
     END
```

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ALLOCATION OF SPENT NUCLEAR FUEL

TRANSPORT CASKS

by

Nancy Haynes Bethel

(ABSTRACT)

The selection of the form of spent nuclear fuel disposition, currently under debate, will precipitate an immediate requirement for spent-fuel transport regardless of the disposition alternative chosen. In this study, a constrained transportation model of the spent fuel cask scheduling problem is formulated with the objective of determining the minimum number of casks required to meet a fixed transport schedule. An iterative search procedure is employed to determine schedules which minimize cask idle time for each required spent fuel cask.

The formulated model and the iterative search procedure are applied to a reference case to demonstrate their utility. An economic analysis of the results was performed to compare the truck and rail transport modes. Results indicate a substantial savings when rail transport is employed. An economic comparison of the cask lease and cask purchase options indicates that cask purchase is preferable for the 23-year planning horizon.