MODELING THE DESIGN AND OPERATIONS OF THE FEDERAL RADIOACTIVE WASTE MANAGEMENT SYSTEM

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ABSTRACT

Many configuration, transportation, and operating alternatives are available to the Office of Civilian Radioactive Waste Management (OCRWM) in the design and operation of the Federal Radioactive Waste Management System (FWMS). Each alternative has different potential impacts on system throughput, efficiency, and the thermal and radiological characteristics of the waste to be shipped, stored, or emplaced. A need therefore exists for a quantitative means of assessing the ramifications of alternative system designs and operating strategies.

In response to this OCRWM need, Science Applications International Corporation (SAIC) and Oak Ridge National Laboratory (ORNL) developed the Systems Integration Operations/Logistics Model (SOLMOD). That model is used to replicate a user-specified system configuration and simulate the operation of that system from waste pickup at reactors to emplacement in a repository under a variety of operating strategies. The model can thus be used to assess system performance with or without Monitored Retrievable Storage (MRS), with or without consolidation at the repository, with varying shipping cask availability, and so forth. This simulation capability is also intended to provide a tool for examining the impact of facility and equipment capacity and redundancy on overall waste processing capacity and system performance. SOLMOD can measure the impacts on system performance of certain operating contingencies. It can be used to test effects on transportation and waste pickup schedules resulting from a shut-down of one or more hot cells in the waste handling building at the repository or MRS. Simulation can also be used to study operating procedures and rules such as fuel pickup schedules, general freight vs. dedicated freight, etc.

INTRODUCTION

Congress has enacted legislation specifying Yucca Mountain, Nevada for characterization as the candidate site for the disposal of spent fuel and high-level wastes. An MRS facility was also authorized if one is warranted. Nevertheless, the exact nature of the facilities making up the FWMS was not specified, leaving OCRWM the job of designing a safe, reliable disposal system. In order to analyze potential design alternatives, operating strategies, and other factors for the FWMS and its various elements, a modeling system consisting of several models and other decision support tools have been developed. These include a Waste Stream Analysis Model (WSA) (1) to establish the quantity, characteristics, and timing of the waste stream entering the FWMS, and a Cost Analysis Capability Model (2) to provide estimates of construction, operations, and other costs for given system designs and operating strategies. The central focus of this OCRWM modeling system is the Systems Integration Operations/Logistics Model (SOLMOD).

SOLMOD is a discrete event simulation model which emulates the movement of radioactive waste through the FWMS --from pickup at reactor pools to emplacement, including all transportation and processing functions. It replicates all elements of a user-defined FWMS configuration and is capable of describing waste moving through that system as a function of quantity, characteristics, timing of input streams, and strategies for system operation. The model is very flexible and permits evaluation of the various operating strategies and system elements such as lag storage at the repository, by simulating the operation of the entire FWMS (or any part of the system) for any user-specified period of time. Model outputs are a series of measurements of the amount and characteristics of waste at selected points in the FWMS and the utilization of resources needed to transport and process the waste. The model output can be analyzed at any desired level of detail and aggregation.

SOLMOD AS A DECISION-SUPPORT TOOL

The design and evaluation of a system for transporting, processing, and storing high level radioactive waste is complex. Radioactive materials, ranging from intact fuel assemblies to activated metals associated with non-fuel hardware, are generated at a number of reactors and other sites throughout the nation. This waste may be transported from across the country, traveling various routes and converging on either the MRS or the repository. Once at the MRS or the repository, flows can follow different paths, depending on type of fuel, condition, amounts and types of materials in related parts of the system, and availability of system resources, equipment, and staff.

At each point in the process, many factors can influence the rate of materials flows. The availability of equipment, staff, or factors such as the difficulty in maneuvering large casks through congested loading areas can constrict or divert waste flow and cause system backups. The sheer variety of forces which can influence flow rates and their interrelationships make it virtually impossible to infer flow levels that could be experienced in actual operation in a simple way. Similarly, in analyzing system design or operating strategies, it is difficult if not impossible to infer the impacts of modifications to one part of the system on the operation of the other components.

SOLMOD can be used to examine the detailed operation of the FWMS or other complex systems. The model simulates movement and interaction of resources (e.g. equipment and staff) and wastes through the FWMS. In conjunction with other models, it can show how different operating schedules and rules, systems configurations, and inventories of equipment and staff impact the performance of processes comprising the FWMS and how they combine to determine overall system performance. SOLMOD can assist in identifying bottlenecks, and can assist in assessing capacity utilization of specific equipment and staff. In short, SOLMOD can help planners assess how well the FWMS will work and, if not, why not.

SOLMOD can also be used as an analytical tool to support several decisions facing OCRWM. In evaluating alternative system configurations, the model will provide an insight into system-operability issues to accompany information on cost, safety, institutional, and other factors which will influence the final decision. For example, for each alternative system configuration being studied, SOLMOD can be used to establish cask fleet requirements for each cask design as well as average and peak utilization of the cask fleet. The utilization of key processes (i.e., loading bays, lag storage, etc.) at the MRS and repository can be established for each alternative, under different operating strategies, and the results compared with maximum utilization limits. This comparison provides a measure of the ability of each configuration to accommodate operating contingencies. Similarly, SOLMOD can be used to measure the utilization of equipment and human resources in the performance of key functions for each alternative system configuration.

The design of a waste package that can meet Nuclear Regulatory Commission (NRC) performance criteria for waste containment, and the assessment of performance of the engineered barrier system, requires, among other things, the identification of the types and characteristics of the waste arriving at the repository for emplacement as a function of time. Those types and characteristics may be derived from data contained in the Characteristics Data Base maintained by Oak Ridge National Laboratory (3). However, the projected characteristics of the waste to be emplaced will be influenced by the configuration of the FWMS and its assumed operating strategy. Thus, SOLMOD can be used to provide detailed information on the age and burnup of waste to be emplaced at the repository, integrated heat, the number and types of assemblies (i.e., the number of BWR and PWR assemblies), and the isotopic loadings of the waste for a wide variety of radioisotopes.

The design of the MRS and the surface and subsurface facilities at the repository requires many unique scoping and design decisions. These decisions may involve trade-offs between the costs and benefits associated with facilities or processes of varying sizes and capacities. Often the analysis necessary to support these decisions deals only with repository facilities when in fact decisions related to the repository may affect the total FWMS. SOLMOD, used in conjunction with other models such as the Cost Analysis Capability Model, provides the capability to measure the impacts of changes to one part of the FWMS on the total system including the repository, MRS, and transportation systems.

SOLMOD can be used to support the analysis of many MRS, transportation, or repository-related design and scoping issues, particularly those requiring cost/benefit trade-off studies. For example, it can be very effectively used to assist in the assessment of system-wide impacts associated with an interruption of waste flows at a major facility. Likewise, SOLMOD can be used to derive system-wide impacts associated with changes in the availability of key processes at the MRS or repository, shipping or storage casks, rail or truck transportation, key equipment such as cranes, as well as other elements essential to the operation of the FWMS.

MODEL DESIGN, STRUCTURE, AND LOGIC

SOLMOD simulates operation of the waste system as a series of connected queues. Each process is a queue which receives waste, performs an operation on the waste, and sends it either to one or more downstream queues or out of the system when all processing is complete. Information on system configuration, waste input to the system, and system performance are kept in files which can be easily modified and/or post-processed.

Design Objectives & Strategy

Eight design objectives for SOLMOD were established after carefully considering OCRWM's simulation needs:

- The simulation must be as close as possible to reality.
- The unique nature of nuclear waste must be recognized and differences among individual assemblies must be preserved.
- Flexible evaluation of different designs must be possible and easy to achieve.
- Detailed as well as high level simulation must be possible and easy for users to control.
- Reporting capability must be user-controllable and must provide for any desired level of aggregation.
- Syntax must be is simple and use the nuclear waste vocabulary.
- There must be a smooth interface with other OCRWM models.
- It must be simple enough to use and not require specialized training in modeling.

Existing logistics modeling software were evaluated in terms of these objectives. While many had impressive capabilities and could meet most of the objectives, no existing language could meet all of them. In particular, existing software had difficulty in tracking the radiological and other properties of the waste and in modeling queues in which operations and branching were based on these characteristics.

Since no software met the full spectrum of requirements, development of a new simulation language was undertaken. Such a language could be specialized to the purposes of nuclear waste system modeling. Specialization would make it possible to include queuing rules unique to nuclear waste and simplify the syntax so that construction of models would require less training than modeling in a general purpose simulation language.

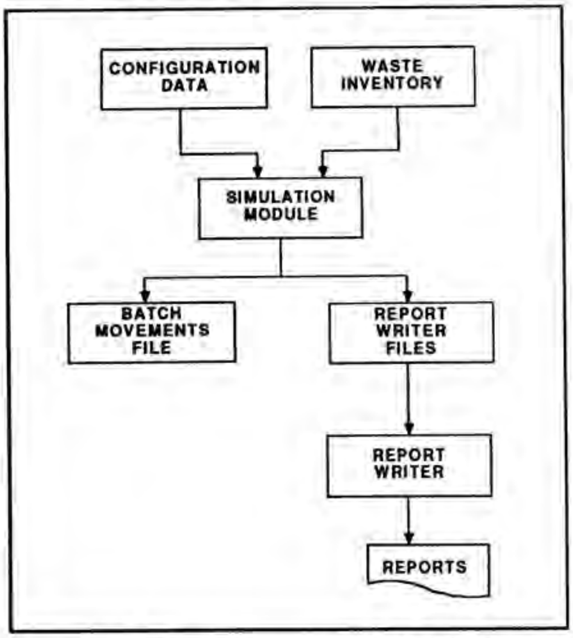

Fig 1. Overall Structure of SOLMOD.

The language was designed in three parts, as shown in Fig. 1:

- A front end prepares input data for the processing module. These data are kept in files which can be saved for reference and modified for subsequent simulations.
- The simulation module models the FWMS as directed by entries in the input files generated by the front end. Inputs consist of an inventory of waste to be processed and the configuration of the FWMS. Simulation module results include a detailed log of each waste movement and summary data on flows and capacity utilizations in each process. Module outputs are stored in a series of files which are used later by the report writer.
- A report writer reads files generated by the simulation module and creates both standard and customized reports.

Data Entry & Results Output

A data entry system, written in a data base language, serves as the front end. This module employs a series of menus and screens which are used to enter data which describe the waste system. The module then creates a file containing this description in the syntax required by the central processing module.

Files created in this way can be modified either with the data entry system or by editing files directly. Any text editor can be used.

The back end of the SOLMOD system is a set of report generators. These report generators are maintained as a separate module so that users can create and modify reports without rerunning the model. As the analyst delves deeper into results, different ways of looking at the data present themselves, and different aspects of the data become important.

Flexibility is especially important when presenting the data graphically. The traditional approach to preparing computer graphics has been to use a command driven language (e.g. Telegraf) to extract data from a file and generate graphs. This approach is very time consuming, with errors and consequent resubmission a common occurrence. Use of an interactive graphics tool, such as those available on microcomputers, is a better choice. To this end, SOLMOD does not include an internal graphics capability. Instead, the report generators are designed to provide data to external interactive graphics packages.

All data needed to run SOLMOD are kept in three types of files: input, output, and scratch. Input files describe waste to be processed and a description of the configuration of the FWMS. Scratch files are used by the model during system simulation. Output files contain simulation results. This ensures several things: alternative systems can be simulated by altering SOLMOD input files rather than by changing source code; minimum run time is achieved by eliminating unnecessary file manipulation; and, results analysis can be based, to a large extent, on post-processing outputs rather than rerunning simulations.

Model output is written to a standard set of output files for further processing. The important point is that <u>all</u> simulation results are directed to these files. Having completed the simulation run, no additional runs are required unless some aspect of the system being modeled is changed via a change in the input data (input file contents). Report writers are used to aggregate results and generate reports containing information needed to analyze the system being studied.

Model Operation

SOLMOD simulates the FWMS by knowing the system's state at each point in time and calculating changes to that state for each time increment. The length of time increment is user-definable. SOLMOD may be run from the very beginning of the time horizon (cold start) or from a user-defined point in time (hot start).

Users must provide two basic types of information, the first of which is a description of the waste system to be modeled. This description represents the waste system as a set of processes and linkages between processes. Rules under which wastes are processed and move between processes are specified. The second set of inputs is an inventory of wastes to be processed, which is based on output from the WSA model. WSA groups wastes into homogeneous batches and schedules pickups in order of priority.

Two main data structures are used to simulate processing. One structure describes the attributes of batches, which are groups of waste materials which move as an entity. The definition of a batch is specified by the user, and usually varies with the processing step. For example, a cask load is a good batch for modeling transportation, while an individual assembly is more appropriate for some operations within the MRS.

The second major data structure describes processes and linkages between processes. Each process description specifies how long the process takes, the capacity of the process (in batches), and the order in which batches are processed. Linkages describe the destination of materials flowing from each process and the conditions under which materials can be moved.

Using these two data structures the model moves through time, from the beginning to the end of the simulation period. Two things are checked at each point in time: which batches are ready to move; and, which linkages between process are open. A batch is deemed ready to move if it has completed the processes in which it currently resides. Determining whether a linkage ("exit" in SOLMOD terminology) is open is more complex and may require the evaluation of many related rules.

When the list of batches which are ready to move and a list of exit paths which are open are complete, the two lists are compared. Batches which are ready to move and which reside in processes have open exits are moved forward. It should be noted that batches can be redefined in the processes. For example, if the cask unloading process handles complete casks, while the disassembly table handles individual assemblies, in moving from one to the other, the batch definition changes from cask to assembly, so that each incoming batch spawns several smaller batches. Once all possible movements have been made, the clock is advanced and cycle repeated. Figure 2 shows the basic processing logic.

In order to achieve a high fidelity simulation of waste movement, a number of options for shaping and constraining waste flows are used. The first of these is the different types of queues. Each process is modeled as one of eight types of queue:

- **First In First Out**: Batches are processed and exit in the order in which they enter.
- **Last In First Out**: Batches exit in the reverse of the order in which they enter.
- **Random**: The order of processing is random--any batch which is ready to leave may leave, regardless of the order in which it entered.
- **Overflow**: Batches are accumulated until a threshold is reached. When the threshold is reached, all of the batches in the process are moved simultaneously.
- **Probabilistic**: In a probabilistic queue, there is more than one exit. The decision about which exit is used is random. The user specifies the relative probabilities of the different exits. All of the standard rules for closing an exit can also be invoked. If the exit selected in the probabilistic calculation is not open, no movement occurs.
- **Split**: A split queue has multiple exits. When materials exits there are flows down each path simultaneously.
- **Sink**: A Sink type queue has no exit. Materials which enter a sink are not available for further processing.
- **Rule Based**: In a rules based queue the user provides a FORTRAN subroutine which establishes the order of batches using an algorithm.

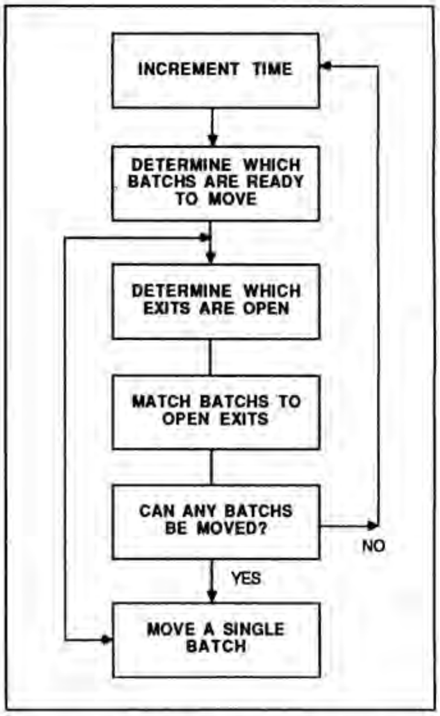

Fig. 2. SOLMOD High Level Logic.

In addition to the control afforded by specifying different types of queues, SOLMOD offers extensive features for constraining flows. These act by shutting down linkages between processes. At each time increment of the simulation clock, rules pertaining to each exit path are evaluated, and paths are determined to be either open or closed. If the path is open, wastes flow. If the path is closed, flow is restricted.

The first constraint on flow is the capacity of the destination process. No flow can enter a process which is currently filled. A second set of constraints are resource constraints. Resources are user-defined entities which are associated with specific processes or links between processes. A user can, for example, define a category of resources (e.g. "CRANE") and specify that a batch requires this resource to move between processes. This movement can not take place if the required resource is not available. (It may, for example, be in use elsewhere.)

Resources can also be allocated to batches in processes. When this is done, a resource which is in use in a process is not available for moving batches between processes. Similarly, a batch can not be moved to a process which requires a resource if that resource is not available.

Annual constraints on flows limit the amount which can flow through a process in a year and different limits may be set for each year and each process. This is useful for ramping the flows up or down to different parts of the system. To allow an orderly shutdown, processes can be linked so that one process shuts down when another reaches its limit. Without this linkage, it would be difficult to implement annual flow constraints.

EXAMPLE SOLMOD APPLICATION

The following example illustrates how SOLMOD can be used to study FWMS design and operating rules. The example is purely illustrative and does not represent a contemplated system or any position taken by the Department of Energy.

Base Case

A base case was created to act as an experimental control and reference for sensitivity studies designed to test SOLMOD's ability to analyze changes in system configuration and operating rules. Highlights of the example system, which includes a repository and an MRS to serve as a storage medium for spent fuel assemblies, are as follows: There are eight unloading bays at the MRS, with two each for BWR casks and two for PWR casks. Truck casks can be unloaded in rail bays if necessary. The repository also has eight unloading bays: two each for PWR and BWR fuel sent from the MRS, two for DHLW, and one each for rail and truck casks sent directly from western reactors.

In the base case, it was assumed that waste from eastern reactors would be held at the MRS without further processing and then removed to the repository at a fixed annual rate. Western reactor waste and DHLW would be sent directly to the repository. All waste canning would be done at the repository rather than the MRS. Finally, it was assumed that all shipments from the MRS to the repository during a given year must be completed before any assemblies are place in long-term MRS storage. Rail casks were given priority over truck casks at MRS unloading bays when both are waiting in order to optimize lag storage use.

The base case operations were simulated over a 13 year period (2000 2012) to obtain baseline results.

Sensitivity Studies

Four major sensitivity studies were performed to evaluate SOLMOD's ability to detect and explain system bottlenecks resulting from changes in the configuration of the FWMS or in its operating rules. The year 2010 was chosen for study.

1. The rule allowing truck cask unloading in rail bays was changed to remove this option, effectively reducing the number of bays at which truck casks can be unloaded.

   Bay utilization, which is the number of hours bays are used as a percent of their availability for use, changed as shown in Table I.

TABLE I
Loading Bay Utilization

Bay Type	Base Case	New Operating Rule
BWR Rail	37%	32%
BWR Truck	27%	39%
PWR Rail	55-60%	32%
PWR Truck	53%	76-80%

   While utilization of BWR bays and the PWR rail bays became more nearly equal, PWR truck bay utilization rose to an unrealistically high level. Clearly, such a change in operating rules should be accompanied by an increase in PWR truck bay availability in order to avoid PWR truck bay bottlenecks.

2. In the second sensitivity study two unloading bays at the repository were assumed to be inoperative. One DHLW bay and one PWR bay receiving casks from the MRS were taken out of operation. This sensitivity study might emulate either of two conditions: bay loss due to equipment failure, or a repository designed with two fewer bays.

   Severe system backup resulted, as shown in Table II.

TABLE II
Sensitivity Study 2 Results

Perf. Measure	Base Case	Reduced Bays
PWR casks unloaded	152	118
DHLW casks unloaded	160	160
PWR bay utilization	59%	92%
DHLW bay utilization	38%	75%

   The same number of DHLW casks were unloaded at the repository but PWR casks unloadings fell significantly. Utilization of the remaining bays for both PWR and DHLW rose, to probably unrealistic levels. However, SOLMOD results pointed to a more significant problem--a backup at the MRS and delay of waste acceptance at the reactors.

   In this simulation, delays which originated at the repository caused PWR wait times to increase, tying up casks. Lag storage at the MRS then filled, causing reactor shipments to wait for unloading at the MRS. At the end of 2010, there were seven PWR truck casks waiting to unload at the MRS because of the bottleneck caused by reducing unloading bays at the repository.

3. A change in repository operating rules to allow PWR MRS casks to share a bay with PWR rail casks from western reactors was modeled as the third sensitivity case. The effect of this rule change is to increase unloading capability at the repository by providing more unloading options. In the base case the bay which unloaded PWR rail cask was only utilized 15% of the time. The sensitivity run demonstrated that utilization of this extra bay would provide sufficient capacity to process all of the MRS fuel shipments.
4. Finally, MRS lag storage capacity was varied from its base case capacity of 1,600 assemblies in order to determine whether any system-wide bottlenecks developed. These sensitivities were analyzed together with analysis of the assumed operating rule which requires all shipments from the MRS to the repository be completed before assemblies are moved from lag to long-term MRS storage.

   Two alternative lag storage capacities were studied: 1,000 assemblies and 500 assemblies. No bottlenecks developed as long as assemblies could be moved from lag to long-term storage and then retrieved during a single year. Thirty-four casks had to be placed in long-term storage then retrieved due to the reduction in lag storage capacity.

As indicated in this hypothetical example, SOLMOD can be a valuable decision-support tool. The model can be used to assess the need for additional capacity by analyzing impacts associated with significant changes in process utilization resulting from operating rule changes. It can also be used to detect bottlenecks and to test system design and resilience to the effects of process interruptions.

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