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A PC-BASED DISCRETE EVENT SIMULATION MODEL OF THE CIVILIAN RADIOACTIVE WASTE MANAGEMENT SYSTEM

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ABSTRACT

A System Simulation Model has been developed for the Department of Energy to simulate the movement of individual waste packages (spent fuel assemblies and fuel containers) through the Civilian Radioactive Waste Management System (CRWMS). A discrete event simulation language, GPSS/PC, which runs on an IBM/PC and operates under DOS 5.0, mathematically represents the movement and processing of radioactive waste packages through the CRWMS and the interaction of these packages with the equipment in the various facilities. This model can be used to quantify the impacts of different operating schedules, operational rules, system configurations, and equipment reliability and availability considerations on the performance of processes comprising the CRWMS and how these factors combine to determine overall system performance for the purpose of making system design decisions. The major features of the System Simulation Model are: the ability to reference characteristics of the different types of radioactive waste (age, burnup, etc.) in order to make operational and/or system design decisions, the ability to place stochastic variations on operational parameters such as processing time and equipment outages, and the ability to include a rigorous simulation of the transportation system. Output from the model includes the numbers, types, and characteristics of waste packages at selected points in the CRWMS and the extent to which various resources will be utilized in order to transport, process, and emplace the waste.

I. INTRODUCTION

The Office of Civilian Radioactive Waste Management (OCRWM) in the Department of Energy (DOE) has sponsored the development of a simulation model to better understand the operation of the Civilian Radioactive Waste Management System (CRWMS). A part of this effort was the development of the System Simulation Model. This model is an extension of previous DOE modeling efforts and includes a number of unique features that were incorporated to meet DOE requirements. Two of the major requirements were the necessity of being able to reference the characteristics of the different types of radioactive waste (age, burnup, etc.) in order to make operational and/or system design decisions, and the ability to rigorously simulate the transportation system.

MASTER

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The System Simulation Model uses a discrete event software language, GPSS,[1] which operates on an IBM/PC. The GPSS software simulates the movement of radioactive waste packages through the CRWMS. The model also estimates the extent to which various pieces of equipment will be used in order to process the waste. It is envisioned that this model will be used to assess the overall operational characteristics of the various elements of the CRWMS by identifying bottlenecks, over or under utilization of equipment, potential storage capacities, etc.

II. MODEL DESIGN AND STRUCTURE

The System Simulation Model simulates the movement of spent fuel assemblies from fuel acceptance by the CRWMS at the reactors to eventual emplacement in a geological formation at a repository. Intermediate waste processing and storage are provided at a monitored retrievable storage (MRS) facility. Facility designs used in the model are based on the CRWMS description used in the FY 1990 DOE Reference System Performance Evaluation (RSPE).[2,3] Five major elements are included in the System Simulation Model: reactor storage facilities, an MRS, a repository, a cask maintenance facility, and the transportation system.

The primary data input for the System Simulation Model comes from the Waste Stream Analysis Model (WSA).[4] These data include the number of spent fuel shipments to be transported from the individual reactor sites annually and the physical and radiological characteristics of each fuel assembly being transported. The characteristics include: assembly type, date of discharge, burnup, enrichment, metric tons of uranium (MTU), and assembly identification (ID). The characteristic information can be assessed at any time during the simulation for making logistical, operational and/or system design decisions. The WSA data file also includes key transportation information including the type of from-reactor cask used to make the individual shipments, the number of assemblies in each cask load, and the appropriate destination.

A storage-only MRS is included in the System Simulation Model. The design of this facility is based on the use of large cement silo storage casks to provide temporary storage. The spent fuel handling portion of the MRS includes two unloading cells. Each cell includes a series of ports for unloading from-reactor casks, loading MRS-to-repository transportation casks, and loading or unloading silo storage casks. Assemblies unloaded from the from-reactor transport casks are transferred directly into an MRS-to-repository transportation cask or a silo storage cask. If neither of these casks are available, the assembly is temporarily placed into the in-cell lag storage facility. The MRS simulation is designed to accommodate a rail cask flow through assumption, in which some of the rail shipments arriving at the MRS will not be unloaded but will be included in the unit trains transporting fuel assemblies from the MRS to the repository. The flow through shipments are identified in the WSA data file.

The repository is assumed to receive spent fuel shipments from the MRS and western reactors. In addition to the spent fuel shipments, additional shipments of defense high level waste will be received from various DOE facilities. In the System Simulation Model, the repository is assumed to contain three unloading ports for spent fuel casks and two unloading ports for defense high level waste casks. After the casks are unloaded, the radioactive waste is placed into waste packages prior to emplacement in the geologic formation. A number of different waste package designs are currently included in the System Simulation Model and other design concepts can easily be added.

The transportation simulation is based on information included in the April 1991 version of OCRWM's Transportation System Data Base (TSDB). Each individual fuel storage facility at the commercial nuclear reactor sites is simulated in the System Simulation Model. This level of detail permits the inclusion of cask dispatching algorithms that direct casks only to reactors where the cask can be loaded immediately, thus avoiding queuing of empty casks at reactors. The dispatching algorithms are also designed to include the definition of periods of time (or windows) when the reactors will not be able to load casks. These periods of unavailability can be used to simulate reactor refueling, maintenance, periods of high load, or periods of inclement weather. These windows can also be used to schedule the cask loading activities for reactors that are prohibited from loading transportation casks when the reactor is operating. Up to three windows can be defined for each reactor in each year of the simulation. The dispatching algorithms can be easily modified to simulate different reactor servicing policies. Simulation of the individual fuel storage locations also permits the addition of reactor-specific processing times when these data become available.

Each transportation cask is maintained annually at a cask maintenance facility that is assumed to be able to process four casks simultaneously. The model assumes that any needed spent fuel cask basket changes will be performed at the cask maintenance facility at the start of the year and that no additional basket changes will occur during the year.

The GPSS/PC software used in the System Simulation Model creates a number of transactions that move through the various facility flow sheets according to prescribed logical conditions (e.g., limits due to facility capacity, availabilities of cranes). The transactions represent the various waste packages moving through the CRWMS. There are many different types of transactions in the model including reactor casks, individual assemblies, MRS storage casks, MRS-to-repository transportation casks, and waste packages. The model allows the different types of transactions to be processed simultaneously, thereby simulating the operational characteristics of the entire CRWMS.

A number of data files identifying the contents (including individual assembly IDs) of each cask, waste package, and lag storage area are generated by the model. Using these assembly IDs, the program can reference the WSA data file to retrieve the physical and radiological characteristics of each assembly. This information can then be used to make processing or container selection decisions based on fuel characteristics.

The model is designed so that the user can easily change such inputs as number of shifts per day, weekend shutdowns, number of cells or other process equipment, the capacity and/or the number of transportation and storage casks, cask loading windows at reactors, and facility locations. One of the more useful features of the GPSS software is the ability to define stochastic variables to represent processing times, equipment availability, etc. A wide range of probabilistic distributions, including the normal, log-normal, exponential, and uniform distributions, can be used to describe the variations being considered. The use of stochastic variables permits the user to make a number of parametric runs to estimate overall system performance and system reliability.

III. MODEL OUTPUT

Three different categories of output are available in the System Simulation Model:

1. On-Screen Windows. GPSS/PC has eight interactive windows that allow the user to observe the progression of the simulated conditions as the model runs. These include a facility summary and a storage summary that show the instantaneous status of each processing and storage facility. The status includes availability, identification of the transaction occupying the facility, and facility usage.
2. Output Files. These files are created during the simulation run and contain a detailed record of cask arrivals at the MRS and the repository and a description of the contents of each cask, storage location, and waste package. Other files include the number of casks waiting to be unloaded at the MRS and the repository.
3. Standard Statistical Report. This report is created at the end of the run and contains several sections.

   a) Block Count - Lists the cumulative number of transactions that have passed through each process in the model and includes the current inventory of each process.
   b) Facilities - Lists the performance data for each facility including number of times used, utilization factor, and average time of use.
   c) Queues - Lists the maximum, minimum, and current number of transactions for each queue. It also shows the average time a transaction had to wait in the queue.

IV. MODEL APPLICATIONS

Two typical applications of the System Simulation Model will be discussed in this paper. The first illustrates how the model can be used to determine the cask fleet size needed to transport spent fuel from the reactor sites to the MRS. The second application shows how the model can be used to examine the operational characteristics of the MRS, including the identification of processing bottlenecks.

A. Estimation of Cask Fleet Size

Calculating the cask fleet size requires an estimate of the amount of time it takes to unload a cask at the MRS or the repository. Cask turnaround time is a function of the cask processing time at the facility plus the time the cask had to wait before the unloading facility became available (queuing time). The System Simulation Model is able to include these details by simulating MRS, repository, and transportation operations simultaneously as discrete, constrained events. The number of from-reactor transport casks waiting to be unloaded at the MRS is shown in Fig. 1. It can be seen from this figure that the size of the queue waiting for entry to one of the MRS unloading cells varies widely during the year, and at times approximately half of the cask fleet was waiting outside of the MRS facility. Typical turnaround times for rail and truck casks are shown in Figs. 2 and 3. In this example, a number of parametric runs were used to determine the size of the cask fleet needed to move approximately 2300 MTU from the reactor sites. This example is based on information extracted from the 1990 DOE RSPE.

The results are summarized in Table 1. The number of cask loads required to transport the fuel from the reactors are shown in the first row. The succeeding rows of the table show the amount of fuel (expressed as cask loads) scheduled to be accepted but not transported for different cask fleet sizes. For this example, 17 truck casks (7 configured for boiling-water reactor, BWR, fuel and 10 configured for pressurized-water reactor, PWR, fuel) and 24 rail casks (9 configured for BWR fuel and 15 configured for PWR fuel) are required to meet the desired spent fuel acceptance rate.

The results in Table 1 were compared with the corresponding fleet sizes (7 BWR truck casks, 9 PWR

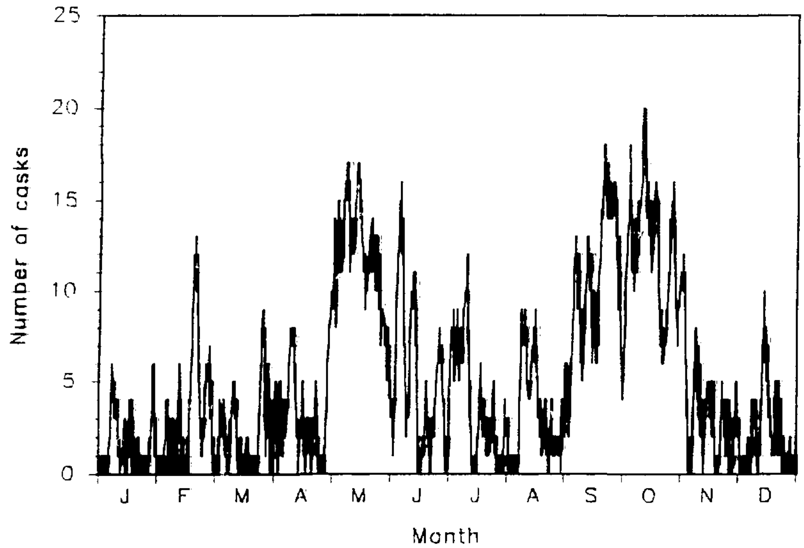

Fig. 1. Number of casks waiting to be unloaded at the monitored retrievable storage.

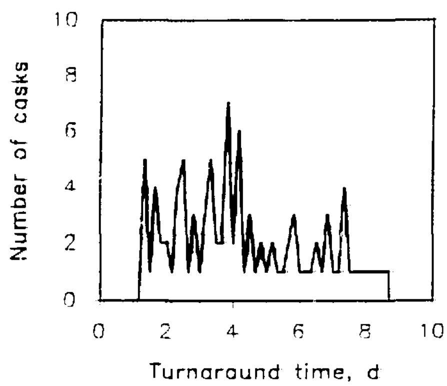

Fig. 2. Typical rail cask turnaround time.

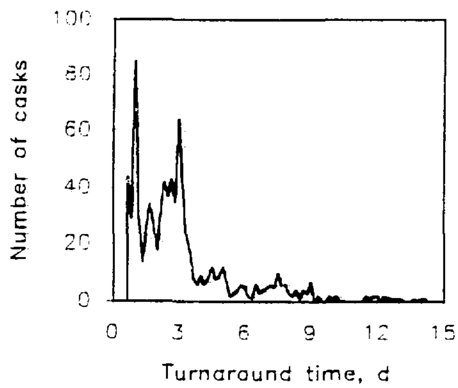

Fig. 3. Typical truck cask turnaround time.

truck casks, 4 BWR rail casks, and 6 PWR rail casks) estimated using the classical techniques outlined in the TSDB. The two techniques generated nearly identical results for the truck cask fleet size estimates. However, the longer turnaround times observed for the rail casks, along with the inclusion of at-reactor loading windows and the more accurate simulation of the MRS operating schedule resulted in the System Simulation Model

Table 1. Transportation cask fleet system performance analysis

	BWR Truck	PWR Truck	BWR Rail	PWR Rail
Number of casks loads to transport approximately 2300 MTU	368	475	49	93
Cask fleet size, run 1	5	8	7	13
Number of casks loads not transported	30	44	13	27
Cask fleet size, run 2	6	9	8	14
Number of cask loads not transported	8	23	5	7
Cask fleet size, run 3	7	10	9	15
Number of cask loads not transported	0	0	0	0

predicting a significantly higher rail cask fleet size. It should be noted that this particular example did not include random variables to predict processing times and the occurrence of equipment outages. It is anticipated that the cask fleet estimates would be even higher if these effects are included.

B. Operational Characteristics of the MRS

Two studies illustrating how the System Simulation Model can be used to investigate operational characteristics of the MRS are included in this section. The first study is a throughput analysis, which itemizes the number of spent fuel casks that can be processed at the MRS under different assumptions. The second study illustrates how the System Simulation Model can be used to evaluate different MRS operational strategies.

1. Throughput Studies. Annual CRWMS acceptance rates are identified in the 1990 Annual Capacity Report.[5] The acceptance rate starts at a low level in 1998 and eventually increases to 3000 MTU/year after the repository has reached its design operating level. The System Simulation Model was used to evaluate whether the MRS design given in Ref. 2 would be able to process spent fuel at this level. For the first portion of this evaluation, it was assumed that the MRS would operate 2 shifts per d, 5 d per week. The MRS design contains two unloading cells. For this evaluation, it was assumed that each cell would be dedicated to the processing of a single fuel type, that is, one cell for BWR fuel and one cell for PWR fuel. The processing time for the cask decontamination process (one of the major steps in the cask unloading process) was represented by the probability distribution shown in Table 2.

Table 2. Cask decontamination probability distribution at the monitored retrievable storage

Process time, h	Probability
1.4	0.80
2.8	0.16
4.2	0.032
5.6	0.008

This distribution represents the probability of having to repeat the decontamination process in order to meet surface contamination requirements. Other MRS processing times were assumed not to vary (deterministic processing times). Unscheduled in-cell crane outages were simulated by a stochastic outage rate. It was assumed that, on the average, the cranes would have an outage after operating for 1000 h and each outage would require approximately 24 h of repair time. Each of these variables was represented with exponential distributions. The cask arrival rates were designed such that, for each type of cask, there would always be an inventory of casks waiting to be unloaded.

The first throughput test assumed that all deliveries to the MRS would be transported in truck casks. Theoretically, if it is assumed that it takes 20 min to unload an assembly and the unloading crane is being used 100% of the time, the MRS should be able to unload a total of 4456 casks—1371 BWR truck casks and 3085 PWR truck casks—annually. As shown in Table 3, the System Simulation Model predicted that the MRS would be able to unload only 1284 casks—600 BWR truck casks and 684 PWR truck casks. This results in an annual throughput rate of approximately 2120 MTU, a rate that is well below the 3000 MTU per year requirement. The lag storage levels showed maximum inventories of 17 BWR assemblies and 4 PWR assemblies.

These low levels indicate that as soon as a cask was moved into an unloading cell, it was immediately able to unload all of its assemblies into a silo storage cask. This conclusion is supported by the reported in-cell crane usage—73% for the BWR cell crane, and 54% for the PWR cell crane. The low use levels indicate that the cranes were sitting idle for significant periods of time, which is further evidence that the processes taking place in the cask preparation area are the limiting factor in determining the number of truck casks that can be unloaded.

A second throughput test was designed in which it was assumed that all of the fuel would be delivered in rail casks. In this case, it is theoretically possible to unload a total of 824 casks—237 BWR rail casks and 587 PWR rail casks—annually. However, the maximum MRS unloading rate observed was a total of 501 casks—186 BWR rail casks and 315 PWR rail casks. This results in a projected annual throughput rate of approximately 4600 MTU.

While this projected rate is above the 3000 MTU design acceptance rate level, it is still well below the theoretical maximum. In this run, both the BWR and PWR in-cell lag storage facilities were completely full more than 95% of the time causing the unloading activities to be suspended while a filled silo storage cask is moved out of the cell and replaced with an empty cask. The rate at which the silo storage casks can be moved in and out of the cell limits the number of rail casks that can be handled. Increasing the lag storage capacities would not have an appreciable effect on the system throughput.

A third test assumed mixed rail and truck deliveries, with approximately 60% of the spent fuel assemblies being transported in rail casks. Under these conditions, the MRS would be able to process a total of 1023 casks—820 truck casks and 203 rail casks. This results in an projected annual throughput rate of approximately 3225 MTU/year. Even though most of the fuel is delivered in rail casks, approximately 80% of the casks being processed are truck casks. Therefore, the operational characteristics of this run are similar to the first run, in which all of the fuel was delivered in truck casks.

The first three scenarios, which are summarized in the top three rows of Table 3, demonstrate that a two-shift operation at the MRS could not consistently process 3000 MTU annually, when only two operational parameters (cask decontamination time and in-cell outages) were modeled stochastically. Otherwise, the data in Table 3 represent ideal conditions with a constant supply of casks on hand waiting to be unloaded. This will not be the case in the real world.

The corresponding throughput data obtained when the MRS is assumed to be operated for three shifts are also shown in Table 3. These scenarios indicate that three-shift operation can increase the MRS throughput, although it is still well below the theoretical maximum.

2. Operating Strategy. A number of operational strategies will need to be evaluated during the design of the MRS. One of these involves the use of the unloading cells. Each of the MRS fuel handling cells can be dedicated to processing a single type of fuel, one cell for BWR fuel and the other cell for PWR fuel; or the cells can be operated as dual purpose cells, where either type of fuel can be processed in each cell.

There are advantages and disadvantages associated with each of these strategies. Dedicated cells simplify operational decisions and minimize in-cell lag storage requirements. The problem with dedicated cells occurs when there is a predominance of one type of fuel being processed at the MRS. In this case, one cell will be heavily utilized while the other cell will have periods of idle time. The alternative strategy of using the unloading cells to process either type of fuel complicates the operational decisions and significantly increases the lag storage requirements. However, the advantage of this strategy is levelling activity when there are a large number of casks of one fuel type waiting to be unloaded. Also, in the event of an extended cell outage, the dual processing strategy would permit the MRS to maintain operation.

Table 3. Monitored retrievable storage throughput analysis

	Number of casks unloaded				
Run	BWR truck	PWR truck	BWR rail	PWR rail	Total MTU
2 shift/truck only	600	684	-[a]	-	2120
2 shift/rail only	-	-	186	315	4600
2 shift/rail & truck	345	475	85	118	3225
3 shift/truck only	887	1037	-	-	3175
3 shift/rail only	-	-	269	467	6850
3 shift/rail & truck	518	712	128	177	4860

[a] - means not applicable.

The impact of these operating strategies was analyzed using the Systems Simulation Model. This analysis utilized a two-shift, 5-d-per-week operating schedule at the MRS and also included a random cask arrival sequence assumption. Since only one type of fuel can be placed in a silo storage cask, when the cells were assumed to unload either type of fuel it was assumed that a silo storage cask would not be brought into the cell until there was sufficient fuel in lag storage and/or in casks being processed to completely fill the storage cask. The use of the lag storage facilities, number of in-cell crane operations, and the amount of time a cask had to wait before being processed at the MRS were used as measures of system performance in this analysis.

When operating as dedicated cells, the lag storage utilization was relatively low. The maximum inventories observed were 17 assemblies for the BWR cell and 7 assemblies for the PWR cell. The maximum lag storage levels increased to approximately 52 BWR and 25 PWR assemblies in each cell when the cells were used to unload either type of fuel.

The increased use of lag storage in the dual processing strategy also increases the number of assembly movements and, hence, the in-cell crane utilizations. A total of 12,580 assembly movements per year is required for the dedicated cell strategy. Eighty-one percent of the BWR assemblies and 70% of the PWR assemblies are moved directly from the transportation cask to the storage cask. The remaining 20 to 30% of the assemblies are stored temporarily in the lag storage area. On the other hand, in the dual processing strategy there were 14,907 crane movements per year, an increase of 18%. In addition, only 60% of the BWR assemblies and 47% of the PWR assemblies were moved directly to the storage casks.

The main impact of these strategies is reflected in the amount of time a cask had to wait prior to being unloaded. For a 3000 MTU acceptance rate containing a high proportion of PWR assemblies, the dual processing strategy reduced the average cask wait time from the 8.31 d observed for the dedicated cell strategy to 4.56 d, thus permitting a higher throughput and a more levelized utilization of the MRS equipment.

V. CONCLUSIONS

The System Simulation Model allows system designers to evaluate a wide assortment of CRWMS configurations and/or facility procedural variations (e.g., the number of unloading cells at the MRS or the number of transportation casks needed). The model will allow the designer to see how system design changes will affect the processing of fuel at the MRS and repository by showing where queues of waste packages waiting to be processed could form and whether these queues would indicate a processing bottleneck. The effects of equipment outages, system outages, and other random events can be studied with the stochastic capabilities of the model.

The ability to run the System Simulation Model on a DOS based PC offers convenience and accessibility to a wide range of users. The model can run on either a 386 or 486 computer and can run a 1-year simulation in less than 10 min. This low turnaround time allows the designer to run studies to rapidly evaluate various system configurations.

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