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Design Concept Evaluation Using System Throughput Model

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Abstract. The U.S. Department of Energy (DOE) Office of Civilian Radioactive Waste Management (OCRWM) is currently developing the technical bases to support the submittal of a license application for construction of a geologic repository at Yucca Mountain, Nevada to the U.S. Nuclear Regulatory Commission. The Office of Repository Development (ORD) is responsible for developing the design of the proposed repository surface facilities for the handling of spent nuclear fuel and high level nuclear waste. Preliminary design activities are underway to sufficiently develop the repository surface facilities design for inclusion in the license application. The design continues to evolve to meet mission needs and to satisfy both regulatory and program requirements.

A system engineering approach is being used in the design process since the proposed repository facilities are dynamically linked by a series of sub-systems and complex operations. In addition, the proposed repository facility is a major system element of the overall waste management process being developed by the OCRWM. Such an approach includes iterative probabilistic dynamic simulation as an integral part of the design evolution process. A dynamic simulation tool helps to determine if:

- the mission and design requirements are complete, robust, and well integrated;
- the design solutions under development meet the design requirements and mission goals;
- opportunities exist where the system can be improved and/or optimized;
- proposed changes to the mission and design requirements have a positive or negative impact on overall system performance and if design changes may be necessary to satisfy these changes.

This paper will discuss the type of simulation employed to model the waste handling operations. It will then discuss the process being used to develop the Yucca Mountain surface facilities model. The latest simulation model and the results of the simulation and how the data were used in the design evolution process will also be discussed. Since the use of dynamic simulation is iterative and integral to the design effort, future activities will also be summarized. The paper will close discussing lessons learned from applying dynamic simulation to designing complex systems, and will discuss what pitfalls to avoid and recommendations for developing flexibility in system model development.

Introduction

In today's world, one of the most difficult questions to answer is, "Is it going to work?" and having an answer that is technically defensible can be difficult if not impossible without the use of a system model. Models will often provide insight into how systems will operate, suggest impacts of proposed changes, and enable system concepts to be evaluated against requirements early in the development phase.

The expansion of risk-informed techniques into nuclear design through a total life-cycle approach offers the opportunity to enhance the safety while reducing both capital and operating costs (Hill 2003). They can also prove to be an effective tool in integrating the design/safety, operations, and financial sectors such that appropriate decisions are made and optimized designs are advanced. A robust and technically defensible risk-informed approach will effectively optimize the design of nuclear and non-nuclear facilities where optimization for cost competitiveness and/or safety is desired.

The Yucca Mountain Project is conducting preliminary design activities to sufficiently develop the Monitored Geologic Repository (MGR) surface facilities design for inclusion in the license application. A system engineering approach is being used in the design process since the proposed repository facilities are dynamically linked by a series of sub-systems and complex operations. In addition, the proposed repository facility is a major system element of the overall waste management process being developed by the OCRWM. Such an approach includes iterative probabilistic dynamic simulation as an integral part of the design evolution process. This is the first phase of the total life-cycle approach.

This paper describes:

- the process used to develop the initial dynamic simulation model of the proposed Yucca Mountain Project surface facilities;
- the benefits of developing a model and the types of results that can be obtained
- the lessons learned from the modeling development
- plans for subsequent modeling activities

MODELING APPROACH

The approach taken to model the MGR surface facilities began with understanding the mission requirements, the functions, the operations, and proposed design concepts. The principal objective of the MGR surface facilities dynamic simulation model was to determine throughput estimates for how much spent nuclear fuel (SNF) and high-level nuclear waste (HLW) could be processed into disposal containers in a given year. Secondary objectives included determining if various design parameters were appropriate and the identification of process constraints (e.g., bottle-necks or pinch-points).

An example of a mission requirement is that the MGR system would be designed to process commercial SNF (CSNF) on a schedule ramp-up rate defined in Table 1 (DOE 2002).

Table 1: Yucca Mountain Commercial SNF Receipt Rates

Year	Commercial SNF Receipt Rate
2010	400 MTHM/yr
2011	600 MTHM/yr
2012	1200 MTHM/yr
2013	2000 MTHM/yr
2014 – Closure	3000 MTHM/yr

The modeling approach involved the following steps:

- Perform Functional Analysis and decomposition (using block flow diagrams and Material Flow diagrams)
- Allocate functions to Conceptual System Architecture
- Develop operational logic for system operation
- Using industry data and expertise estimate process times (best, nominal, and worst-case distributions)
- Analyze processes to determine if physical dependencies exist
- Develop the dynamic simulation model using the GoldSim (Golder 2003) simulation software
- Provide feedback and results to management and the design organization
- Iterate as new information becomes available and as design concepts evolve

Since the preliminary design of the facility is in its early stages and includes several first-of-a-kind systems, very little information existed to provide the technical bases for the model. The existing design information was supplemented by estimates from engineers from multiple disciplines (e.g., fuel handling, welding, operations). A facilitated approach that fostered cross-discipline integration resulted in operational logic and process times that were felt to be reasonable.

The high level functions of the MGR surface facilities are shown in Table 2.

Table 2: MGR Surface Facilities High-Level Functions

Transportation of Casks	Cask Receipt	Dry Transfer & Waste Handling	Welding and WP Closure	Waste Emplacement

These functions were then further decomposed and allocated to Conceptual System Architecture as shown in the example on Table 3.

Table 3: Functional Decomposition and Allocation

Cask Receipt Facility	Dry Transfer Facility
Function: Cask Acceptance Process Duration: (90/150/240 Minutes)	Function: Move/Up-Right Cask Process Duration: (255/390/540 Minutes)
• Security Reviews Authorization & Conducts Security Inspection • Conduct Cask Visual Inspection • Verify Receipt Records Comply with Shipping Manifest • Remove Personnel Barrier • Conduct Radiation & Contamination Survey of Carrier Vehicle	• Engage Prime Mover • Move SSR/Cask from Buffer Area to Process Building • Open Exterior Airlock Door • Move SSR/Cask into Airlock • Close Exterior Airlock Door • Open Interior Airlock Door

In addition to understanding the MGR System Requirements, the modeling requirements were developed to ensure the dynamic simulation model would accurately simulate processes, provide user flexibility, obtain representative results of key design parameters. Examples of some of these requirements included:

1. Provide ability to evaluate variable waste stream characteristics
   - Different waste types (e.g, Boiling Water Reactor (BWR), Pressurized Water Reactor (PWR)
   - Waste receipt rate
   - CSNF thermal characteristics (waste streams with varying average CSNF assembly thermal outputs, cooler – hotter)
2. Monitor key design parameters
   - Internal CSNF staging requirements
   - Thermal characteristics of loaded waste packages and aging casks
   - Welding cell utilization
3. Monitor sub-process performance
   - Welding cell utilization
   - Fuel assembly and canister transfer crane usage
4. Monitor process "bottle-necks" or "pinch points"
5. Provide flexibility to evaluate different design options and operational scenarios:
   - Different transportation modes (rail shipment verses truck)
   - Types of facilities operational
   - Number of process lines available
   - Number of weld cells available
   - Waste campaigning

Dynamic System Model Description

The current conceptual design of the MGR surface facilities consists of

- a cask receipt building for processing transportation casks
- two dry transfer facilities (DTF 1 and DTF 2) for transferring bare and canisterized wastes into either waste packages or aging casks (AC)
- a canister handling facility (CHF) for transferring canisterized wastes into waste packages (WP)
- a facility for aging CSNF that is too hot to be emplaced in the proposed repository,
- a remediation building for processing off-normal wastes
- balance of plant facilities

The dynamic simulation model includes all of these facilities, except for the remediation building and the balance of plant facilities.

A very simplistic approach is used to thermally manage CSNF. A fuel assembly thermal output threshold is established for both BWR and PWR SNF. These thresholds can be changed. Any fuel assemblies having a thermal output above this threshold are assigned for loading into an aging canister and placed in the aging facility. Those fuel assemblies having a thermal output equal to or below this threshold are assigned for loading into a waste package for emplacement in the repository.

The overall process flow is shown in Figure 1. One of the most important components of the model is the process selection step. It is at this phase of the modeling effort that determines the logic for what processes will be performed next.

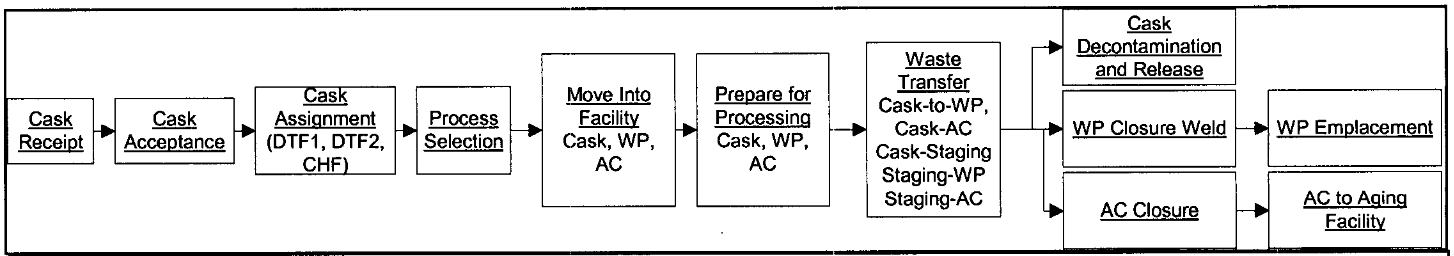

Figure 1. Yucca Mountain Surface Facility Dynamic Simulation Model General Process Flow

Identifying the exact CSNF waste stream expected to arrive at the proposed repository is not currently possible. However, the design needs to accommodate the range of CSNF waste characteristics that could potentially arrive. Thus, the model assumes a series of bounding waste streams, ranging from a cool waste stream (oldest fuel first) to a hot waste stream (youngest fuel first, aged greater than 5 years). It is assumed that the CSNF arrives randomly within a given year at rates given in Table 1. U.S. Department of Energy owned spent nuclear fuel and high level waste, 7000 MTHM in canisters, are assumed to arrive randomly over the assumed 30 year operational period.

The cask assignment step assigns transportation casks to the DTFs and/or the CHF. If a scenario is selected where the CHF is operational, all casks containing canisterized wastes are assigned to it, else they are assigned to the DTFs. Casks containing both BWR and PWR CSNF are assigned to each DTF unless the campaign scenario is selected. In that scenario BWR CSNF is assigned to DTF1 and PWR CSNF is assigned to DTF2.

Process selection is based on three priorities, in descending order:

1. Minimize the amount of bare fuel and canisters in the staging area;
2. Maximize waste package loading;
3. Maximize aging canister loading;
4. Maximize cask processing.

Given these priorities, the following logic is evaluated to select the next processing step.

1. If there is sufficient inventory in the staging area to load a waste package, then load the waste package from the staging area alone (do not bring in a cask for processing). Else;
2. If there is sufficient inventory in the staging area to load an aging canister, then load the aging canister from the staging area alone (do not bring in a cask for processing). Else;
3. If there is sufficient inventory in the staging area and the largest available cask to load a waste package, then load a waste package from the staging area and that cask (bring in both a waste package and a cask for processing). Else;
4. If there is sufficient inventory in the staging area and the largest available cask to load an aging canister, then load an aging canister from the staging area and that cask (bring in both a waste package and a cask for processing). Else;
5. If the staging area has room to accept waste, then load the staging area from a cask. Else
6. Do nothing.

Note that in order to load a CSNF waste package, the model tracks the inventory of CSNF in both the casks and staging area with thermal output equal to or below the thermal output threshold. In order to load an aging cask, the model tracks the inventory of CSNF in both the casks and staging area with thermal output above the thermal output threshold. This is done for each waste type (BWR/PWR bare fuel and canisterized waste).

In addition to the logic steps above, the model determines whether the facility is capable of making another process selection. For example, if a cask and a waste package are being prepared for processing in a DTF, it is not possible to begin another process until those areas in the DTF have been cleared. These types of logic checks are used throughout the model to ensure proper process sequencing.

Once a selection is made, the casks, waste packages, or aging canisters are moved into the facility (either the DTFs or the CHF). They are then up-righted and moved into the preparation area. Here they are made ready for subsequent processing. From here they are moved into the hot cell and docked into the waste handling ports.

Bare CSNF fuel or canisters are transferred from the stating area to a waste package, from the staging area to an aging canister, from casks to waste packages, from casks to an aging canister, or from casks to the staging area. Once a cask is emptied, it is un-docked and moved into the decontamination area where it is made ready for release. Full waste packages are moved to the welding area where they are welded closed, inspected, and then released for emplacement into the repository. Full aging canisters are moved into an area where they are closed and subsequently released for transport to the aging facility.

As discussed above, logic checks are used to ensure proper process sequencing. For example, a cask that is prepared for processing cannot be moved into the hot cell until one of the docking ports is open.

Dynamic System Model Results

This section summarizes the types of results obtained from the model. They do not represent the U.S. Department of Energy's final system performance results. They are provided to demonstrate the types of results that can be obtained from such a model and how they can be used to improve the capabilities of the facilities through design.

The model was first used to evaluate the scenario where all facilities are operational and receiving waste at the maximum receipt rate (see Table 1). Six month simulations were conducted assuming all facilities had 100 percent availability. The projected processing rates of commercial SNF through the facilities are shown in Table 4. The performance of system, in terms of cask, waste package, and aging cask processing, is shown in Figure 2 for the mostly rail – hot waste stream case.

Table 4: Projected facility processing rates

Transportation Mode / Waste Stream	Casks Arrived	Casks Returned	Waste Processed (MTHM)
Mostly Rail – Cool	209	207	1676
Mostly Truck – Cool	1166	642	643
Mostly Rail - Hot	507	375	1209
Mostly Truck - Hot	1537	616	767

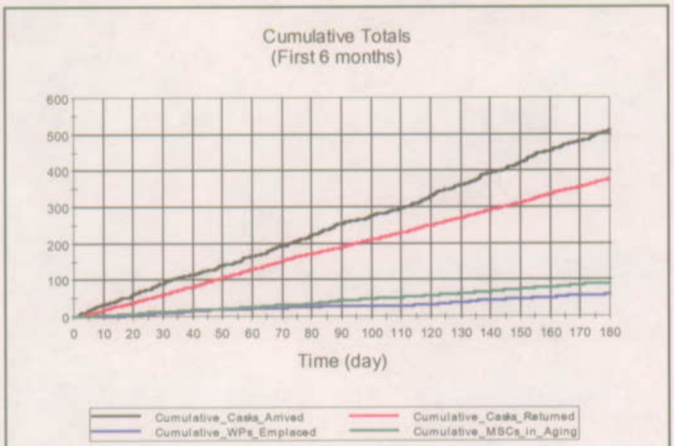

Figure 2. Facility Processing for the Mostly Rail – Hot Waste Stream Case

Facility processing rates largely depend on the mode by which commercial SNF is transported to the repository. Rail casks are considerably larger than truck casks. For example, the largest BWR rail cask considered in the model can transport 68 commercial SNF assemblies while the largest BWR truck cask can only transport nine. A larger number of truck casks needs to be processed through the facility in order to load an identical amount of fuel assemblies from a rail cask into either a waste package or an aging canister. Secondly, since truck casks are considerably smaller than either a waste package or an aging cask, a larger number of fuel assemblies must first be loaded into the staging area before a large enough inventory exists to load either a waste package or an aging canister. This results in more multiple handling of fuel assemblies, which lowers the processing rates.

The total amount of waste processed in six months shown in Table 1 is loaded into waste packages for the cooler waste stream. In the case of a hotter waste stream, the commercial SNF is loaded into both waste packages and aging canisters, as shown in Table 5.

Table 5: Total Six-month Commercial SNF Processing

Transportation Mode / Waste Stream	Waste Processed (MTHM)	Into Waste Packages (MTHM)	Into Aging Canisters (MTHM)
Mostly Rail – Cool	1676	1676	
Mostly Truck – Cool	643	643	
Mostly Rail - Hot	1209	247	962
Mostly Truck - Hot	767	307	460

Tables 4 and 5 show that the thermal characteristics of the waste stream also have a significant impact on facility processing rates for the mostly rail transportation scenario. There are three factors that result in decreased processing rates for a hotter waste stream with the mostly rail transportation mode. First, it is assumed that fuel assemblies with higher thermal output must be transported in either smaller transportation casks or in transportation casks containing less than their physical capacity. As in the case of rail versus truck transportation modes for the cooler waste stream, more casks need to be processed.

Secondly, more multiple handling of fuel assemblies is required for hotter waste streams. Casks containing cooler, hotter, and a mix of cool and hot commercial SNF assemblies arrive. In order to load a waste package or an aging cask, it is necessary to place both hotter and cooler fuel assemblies into the internal staging area to build-up sufficient inventories such that a waste package or aging canister can be filled. There is less loading directly from a cask into a waste package or aging canister as is observed when loading waste packages from a cooler waste stream. This is evident in Table 6, which shows the maximum amount of BWR and PWR fuel assemblies placed in the internal staging area for the different transportation mode / waste stream scenarios. The peak internal staging inventories were determined from tracking the inventory in the staging area, shown in Figure 3 for the mostly rail – hot waste stream case.

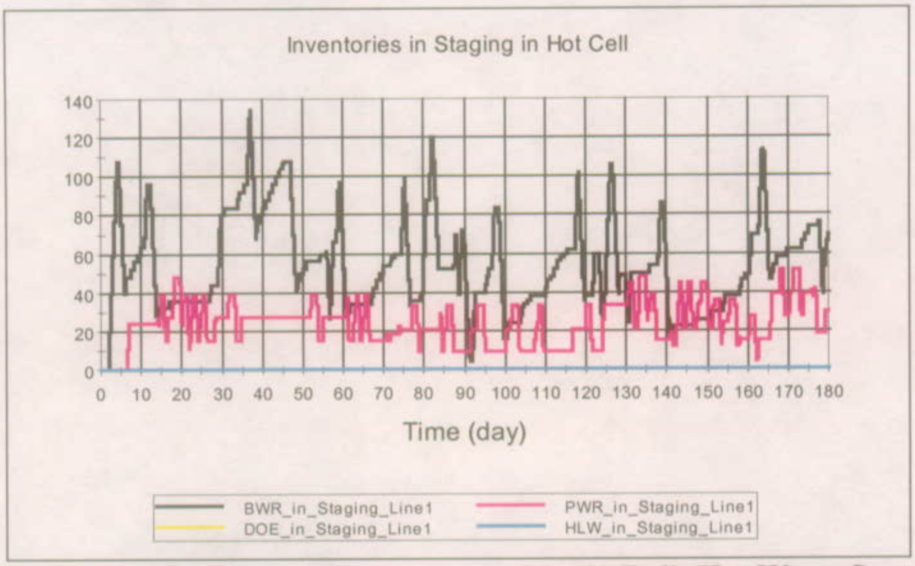

Figure 3. DTF 1 Internal Staging Inventory, Mostly Rail- Hot Waste Stream Case

Table 6: Peak Internal Staging Inventory of Fuel Assemblies

Transportation Mode / Waste Stream	BWR	PWR
Mostly Rail – Cool	50	29
Mostly Truck – Cool	47	23
Mostly Rail - Hot	135	48
Mostly Truck - Hot	109	52

The current dry transfer facility design has two cask docking ports and two waste transfer lines. For a cooler waste stream, two casks and two waste packages can be docked simultaneously, resulting in efficient transfer of waste from the casks and staging areas to the waste packages. However, for the hot waste stream, aging canisters must be processed through the cask docking ports. This effectively eliminates one cask docking port and does not permit any transfer of fuel assemblies to a waste package while an aging canister is being loaded.

A different trend is seen for the mostly truck transportation mode where more waste is processed through the facility for a hotter waste stream. This is due to the assumption that the hottest PWR fuel assemblies are transported in a 12-assembly rail cask (or a 12-assembly heavy-haul truck cask). This larger cask results in a smaller number of casks needing to be processed and less multiple handling of PWR fuel assemblies to load a PWR aging cask. This results in a slight increase in process efficiency for a hotter waste stream.

Besides estimating waste processing rates, such a model is also useful in estimating cask processing rates. This is an important interface to the transportation system. Figure 4 shows the model's two week rolling average rate that casks both arrive at the repository and are ready to return to the transportation system for the mostly rail, hot waste stream case. It can be seen that the arrival rate is higher than the return rate as is also shown in Table 4. The assumption of an infinite supply of casks results in a backlog of casks at the repository. In reality, the cask supply will be constrained and the transportation system would have to wait until these casks are processed through the repository surface facilities prior to transporting additional wastes in them to the repository. Only in the case of the mostly rail, cool waste stream case would no backlog of casks occur, as shown in Table 7.

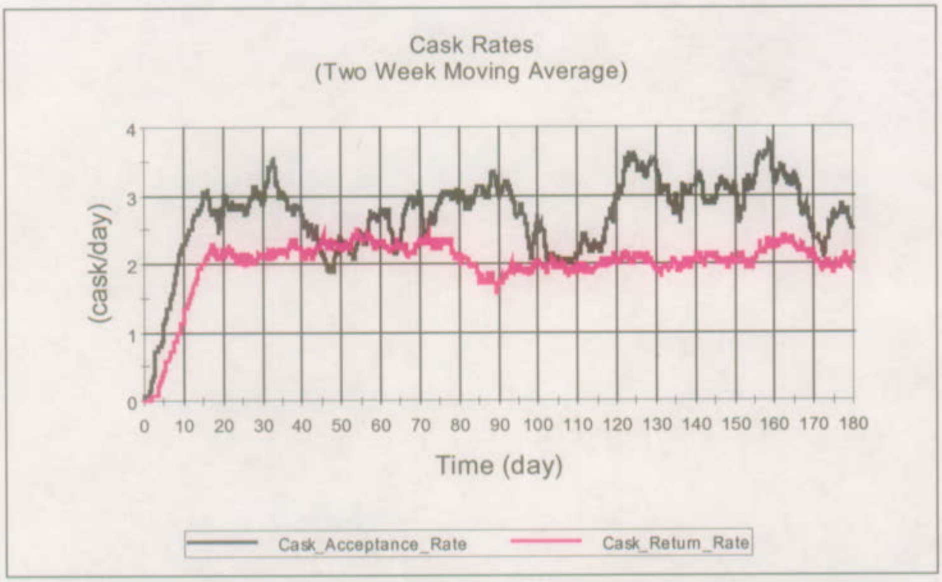

Figure 4. Cask Arrival and Return Rate, Mostly Rail - Hot Waste Stream

Table 7: Cask Arrival and Return Rates (two week rolling-average)

Transportation Mode / Waste Stream	Cask Arrival Rate (day^{-1})	Cask Return Rate (day^{-1})
Mostly Rail – Cool	1.0 – 1.5	1.0 – 1.5
Mostly Truck – Cool	6.0 – 7.0	3.0 – 4.0
Mostly Rail - Hot	2.0 – 5.0	2.0 – 2.5
Mostly Truck - Hot	8.0 – 10.0	3.0 – 4.0

Another important interface result is the rate that waste packages are made ready for emplacement in the repository. Current plans call for concurrent construction of the repository sub-surface facilities and waste package emplacement. Estimates of waste package production can help determine: 1) the needed construction schedule such that the repository can have sufficient capacity to accept loaded waste packages; or 2) whether a waste package staging area is needed. This model assumes that the sub-surface facilities have sufficient capacity to accept loaded waste packages.

A similar interface result is the rate that aging canisters are made ready for placing in the aging facility. A feature not included in this model is the fact that after sufficient aging, these canisters will be brought back into the dry transfer facilities and their contents transferred into waste packages. The processing of these aging casks will occur concurrently with the processing of the contents in newly arrived transportation casks. This will result in a reduction in the rate that casks can be processed through the facilities.

The two-week rolling-average waste package production rate for the mostly rail, cool waste stream case is shown in Figure 5. An interesting feature for this case is that the waste package production rate looks very similar to the cask arrival/return rates indicating that the arrival of casks at the facility is limiting the throughput. In fact, at 100 percent availability, the facility can process more than 3000 MTHM of commercial SNF as required in Table 1.

The waste package and aging canister production rates for all of the scenarios are shown in Table 8. The mostly rail transportation scenario, cool waste stream scenario results in the fastest production of filled waste packages. The production of waste packages slows considerably for hotter waste streams as a result of having to load aging canisters.

Table 8: Waste Package and Aging Canister Processing Rates (two week rolling-average)

Transportation Mode / Waste Stream	Waste Package Production Rate (week^{-1})	Aging Canister Production Rate (week^{-1})
Mostly Rail – Cool	6 – 12	
Mostly Truck – Cool	4 – 6	
Mostly Rail – Hot	1 - 5	3 – 5
Mostly Truck - Hot	2 - 4	1 - 3

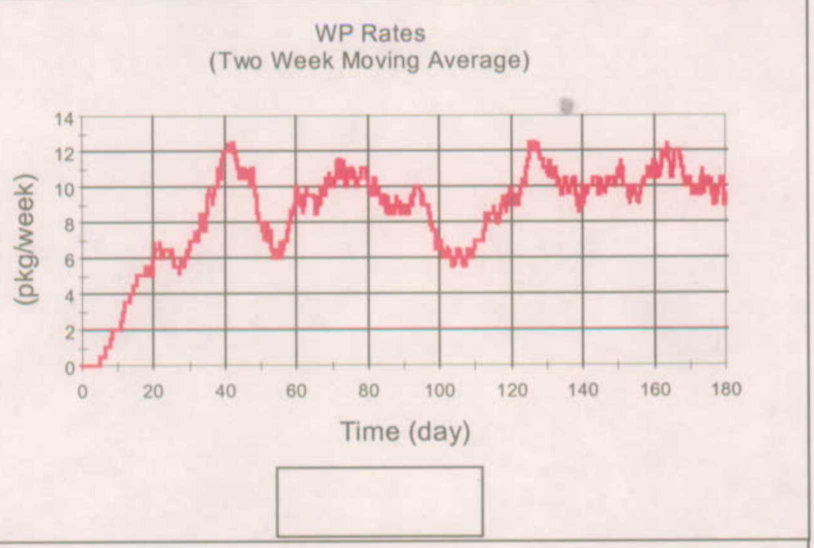

Figure 5. Waste Package Processing Rate, Mostly Rail - Cool Waste Stream

Design parameters can also be analyzed using a dynamic simulation model. Internal staging requirements, as discussed above, depend on the waste stream that will ultimately arrive and the thermal management strategy that will be used to process commercial SNF with varying thermal output. However, it can clearly be seen that a larger internal staging capacity will be needed to manage hotter fuel assemblies.

Another design parameter of interest is the utilization of the waste package welding cells. The current design calls for three independent waste package welding cells in DTF 1 and four in DTF 2. Figure 6 shows the utilization of the welding cells in DTF 2 for the mostly rail, hot waste stream case. Weld cell utilization for all of the scenarios is shown in Table 9.

The welding cells are most effectively utilized for the mostly rail, cool waste stream case. In several instances, loaded waste packages must wait in the hot cell until a weld cell becomes available. This demonstrates that the welding process is one of the pinch-points for this transportation mode – waste stream scenario. The other three scenarios result in the welding cells sitting idle for periods of time.

Figure 6. Weld Cell Utilization, Mostly Rail, Hot Waste Stream

Table 9: Waste Package and Aging Canister Production Rates (two week rolling-average)

Transportation Mode / Waste Stream	Number of Welding Cells In Use DTF 1	Number of Welding Cells In Use DTF 2
Mostly Rail – Cool	1 - 3	1 - 4
Mostly Truck – Cool	1 - 2	1 - 2
Mostly Rail - Hot	0 - 2	0 – 2
Mostly Truck - Hot	0 - 1	0 - 1

Lessons Learned

Several lessons learned were revealed as a result of developing the initial dynamic simulation model of the MGR surface facilities. While many of these are specific to the throughput model, many lessons can be applied generically for other model development endeavors.

Highlights of these lessons are listed below:

- The operational logic used in the model has a significant impact on system performance (e.g., waste package production rates, cask return rates). Although experts from various disciplines were consulted in developing the model, different facility operating logic may ultimately be used.
- Process times have a significant effect on system performance. The process times used in this initial model are only estimates. This is appropriate given the early stage of the design of the facilities. As the design advances, these process times should have strong technical bases including detailed analyses and operation experience. Process times can be easily modified as better estimates become available and are confirmed.
- The model results indicate that the ability to process smaller casks through the facilities limits system performance for the mostly truck cask arrival scenario. The surface facilities are much more efficient at processing waste when it arrives in larger rail casks.
- The time required to transfer waste (bare fuel or canisters) in the hot-cell has the most significant impact on system performance.
- The characteristics of the waste stream, in particular the thermal output of the arriving commercial spent nuclear fuel has a significant impact on system performance.
- The thermal management strategy utilized will have a significant impact on system performance.
- Understanding which parameters and variables control system performance and including them in the model allows a quantitative assessment of how they truly affect system performance. This also results in a flexible model that can easily be changed to incorporate new or changing information.
- A top-down approach should be used where models are as simple as possible. This permits the focus to be on overall system performance, rather than focusing on lower-level factors. Additional detail can be added based on the results and the availability of additional information.
- The process of evaluating functions, operations, and logic in the development of such a model is of equal benefit as the results it generates. This fosters cross-discipline integration and leads to the increased understanding of system behavior

There are several benefits to developing a dynamic simulation model of such a complex system, including:

- Provides a quantitative tool for estimating system performance,
- Provides an excellent framework to aid in cross-discipline integration,
- Provides a tool to test various operational logic,
- Provides a tool to evaluate potential design changes,
- Provides insights into how a system would need to be operated
- Provides validation of system/subsystem requirements

Users of such a dynamic simulation model and its results must also take care so as not to encounter pitfalls that include:

- Such a model is only good as the data used as input (i.e., garbage in - garbage out). If the supporting data are of questionable value, then the results themselves are questionable.
- Results generated should be used within their context. The development of such a model requires many assumptions. Not understanding the assumptions beneath the model could cause the results to be used inappropriately and perhaps erroneously.
- Over reliance on model results may lead to shortfalls in the design. Although there are tremendous benefits of using dynamic simulation, it should be viewed as one of several useful tools to aid in the design process.

Acknowledgments

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Biography

Mr. Sequeira is employed by Booz Allen Hamilton in the position of surface facility design lead for the Management and Technical Support Services contractor team supporting the U.S. Department of Energy Office of Civilian Radioactive Waste Management. He received his B.S. in electrical engineering from California State University of Long Beach in 1986, and his Master's in Engineering from California State Polytechnic University in 1993. He has experience in aerospace electrical system design, system analysis, system requirements, electrical circuits modeling, and nuclear handling design and operations.

Dr. Mark Nutt is employed by Golder Associates Inc. in the position of technical teams coordinator for the Management and Technical Support Services contractor team supporting the U.S. Department of Energy Office of Civilian Radioactive Waste Management. He received B.S., M.S., and Ph.D. degrees in Nuclear Engineering from Iowa State University in 1985, 1989, and 1995. He has experience in nuclear design and the application of probabilistic performance/risk assessment techniques to evaluate the long-term performance of radioactive waste disposal facilities.