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ABSTRACT

The unloading of spent fuel from the Experimental Breeder Reactor-II (EBR-II) for interim storage and subsequent processing in the Fuel Cycle Facility (FCF) is a multi-stage process, involving complex operations at a minimum of four different facilities at the Argonne National Laboratory-West (ANL-W) site. Each stage typically has complicated handling and/or cooling equipment that must be periodically maintained, leading to both planned and unplanned downtime. A program was initiated in October, 1993 to replace the 330 depleted uranium blanket subassemblies (S/As) with stainless steel reflectors. Routine operation of the reactor for fuels performance and materials testing occurred simultaneously in FY 1994 with the blanket unloading. In the summer of 1994, Congress dictated the October 1, 1994 shutdown of EBR-II. Consequently, all blanket S/As and fueled drivers will be removed from the reactor tank and replaced with stainless steel assemblies (which are needed to maintain a precise configuration within the grid so that the under sodium fuel handling equipment can function). A system modelling effort was conducted to determine the means to achieve the objective for the blanket and fuel unloading program, which under the current plan requires complete unloading of the primary tank of all fueled assemblies in 2 1/2 years. A simulation model of the fuel handling system at ANL-W was developed and used to analyze different unloading scenarios; the model has provided valuable information about required resources and modifications to equipment and procedures. This paper reports the results of this modelling effort.

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I. INTRODUCTION

The EBR-II is a 62.5 MW(th) liquid metal reactor operated by ANL-W for the United States Department of Energy. Full power operation was achieved in 1964; the reactor has operated in a variety of configurations depending on the programmatic mission. From 1983 to 1994, it operated as the Integral Fast Reactor (IFR) prototype, as well as serving as an irradiation test facility for fuels development and structural materials damage studies. A three year program was initiated in October, 1993 to replace the 330 depleted uranium blanket S/As with stainless steel reflectors. Routine operation of the reactor for fuels performance and materials testing occurred simultaneously with the blanket unloading. Beginning October 1, 1994, the reactor will be shut down and all fueled S/As from the primary tank will be replaced with stainless steel assemblies. The inventory in the primary tank of fueled S/As (including blankets) that are to be transferred is

103 driver S/As (including control rods)
28 experimental S/As
321 depleted uranium blanket S/As

for a total of 452 S/As to be removed. The schedule requires that these S/As be removed in 2 1/2 years, which necessitates a rate of 14 transfers per month, or 167 per year. This rate is at least 50% greater than any historical experience; the purpose of this modelling is to determine if (a) the rate is achievable, and (b) what modifications to procedures or equipment are required to achieve the goal.

The unloading of spent fuel from EBR-II for interim

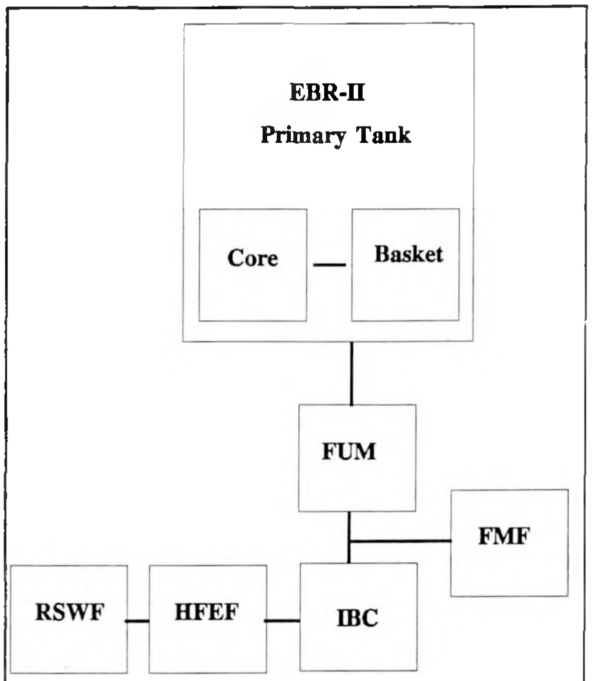

Figure 1.
Fuel Handling Process at ANL-W

storage and subsequent processing in the FCF is a multi-stage process, involving complex operations at a minimum of four different facilities at the ANL-W site. The process is shown schematically in Figure 1. Specifically, the path to temporary storage in the Radioactive Scrap and Waste Storage Facility (RSWF) (where S/As are stored awaiting processing in FCF) consists of five stages: (1) transfer from the reactor grid to the in-tank storage basket, (2) transfer from the storage basket to the wash station (to wash residual sodium from the S/A) using the Fuel Unloading Machine (FUM) to load a S/A into the Inter-Building Cask (IBC), (3) transfer from the wash station via the IBC to the Hot Fuel Examination Facility (HFEF) where most S/As are placed in pits that are actively cooled, (4) transfer from the cooling pits to air storage racks (passively cooled), and (5) disassembly and packaging in HFEF for interim storage at RSWF in pits. Each stage has a set of criteria that must be satisfied before a subassembly can be received. The criteria are based on decay power and age of the S/A: decay power to ensure adequate cooling will be available, either active or passive, and age to ensure that certain isotopes have decayed to minimize the source term in facilities outside the reactor. Additionally, each stage typically has complicated handling and/or cooling equipment that must be periodically maintained, leading to both planned and unplanned downtime.

A mathematical model of the fuel transfer process from EBR-II to RSWF was constructed. Maintenance records were examined to derive statistical models of the failure rates and downtime of various pieces of equipment in the process. Information such as this allows a quick identification of the critical components of the process, which in turn enables management to focus on upgrades to equipment that can truly improve the process. Operations logs were examined to attempt to derive quantitative estimates of the amount and statistical distributions of time required to perform various tasks in the process. This allows management to determine staffing requirements to improve the process (if an improvement in rate is indeed necessary). The criteria for receipt of subassemblies at the facilities were included. For example, to safely ensure adequate cooling in the air storage racks at HFEF, the decay power of a subassembly must be below 150 watts, which translates into a decay time which depends on the S/A's position in the reactor grid. Criteria such as these are similar to flow restrictors in fluid dynamics, limiting the transfer rate regardless of staffing or equipment reliability. The restrictions due to these criteria are subassembly dependent; the model allows parametric studies to be performed to obtain the optimum unloading sequence given constant staffing and reliability parameters.

II. DESCRIPTION OF THE FUEL HANDLING SYSTEM

Fuel handling operations in EBR-II are classified as unrestricted and restricted. Unrestricted fuel handling refers to transfers between the reactor grid and the storage basket, both within the primary tank. Unrestricted fuel handling requires that the reactor be shutdown. In restricted fuel handling, which can be performed when the reactor is in operation, the movement of S/As is between the IBC and the storage basket via the FUM. The performance of the fuel handling system during the normal operation of the reactor with a 70% plant factor has been addressed in previous work by these authors [1-2]. This article is directed to the reactor shutdown scenario in which unrestricted fuel handling is not limited by the plant factor. The following operations are performed:

Mode 1: A stainless steel S/A is transferred from the Fuel Manufacturing Facility (FMF) building to the basket;

Mode 2: A spent fuel S/A is removed from the core and transferred to the basket. This transfer creates an empty location in the core;

Mode 3: The stainless steel S/A is removed from the basket and placed in the empty location in the core;

Mode 4: Upon verification of availability of the IBC for transfer, a spent fuel S/A is removed from the basket in the reactor tank and is transferred to the cooled Inter-Building Cask (IBC).

A S/A loaded in the IBC for transfer out of EBR-II undergoes the following sequence of operations:

- Decontaminate the IBC cask to remove surface contamination and place it in the air-lock between the EBR-II building and the FCF building;
- Move the cask to the IBC wash station in the FCF building, and perform radiation surveys and preparation tasks to prepare the wash station for the wash;
- Connect assorted hoses, purge the system, humidify, wash and dry the S/A to remove sodium;
- Transport the IBC containing the washed S/A to HFEF via truck and unload the S/A into the hot cell of HFEF;
- Transfer the S/A to a cooling pit (if active cooling is required) and use the truck to return the empty IBC cask to FCF;
- Remove any residual moisture from the IBC cask in the IBC wash station using the driers and return the dried cask to the EBR-II reactor building.

Limits on thermal loading of the stored S/A typically require that a S/A be cooled for some time prior to being transferred to RSWF. This time is determined by the decay power of the S/A, which in turn is governed by the type of S/A and its location in the core. The capacity of the HFEF facility is 40 pits with cooling capability and 5 racks of 10 positions each, without active cooling capability. Table 1 shows the approximate residence time in the cooled pits and uncooled racks as a function of the type of subassembly. As can be seen, the residence time will play a major role in the HFEF fuel handling capacity in the first year following the reactor's shutdown. It also demonstrates that the optimal path for fuel unloading will be to start with the blankets, as they require no cooling time prior to transfer to RSWF.

The sequence of operations that are involved in transfers of S/As from HFEF to RSWF are as follows:

- After a S/A has remained in the cooling pits for the required amount of time, the S/A is transferred to an uncooled rack;
- After the S/A has decayed further, it is transferred to the dismantling area. Fueled S/As require that individual fuel pins be removed from the S/A hardware (hex can) before packaging for storage; they are dismantled using the Vertical Assembler Dismantler (VAD). Blankets and hardware scrap are prepared for packaging by using a Cutoff Saw (COS); the top and bottom fittings of a blanket S/A are removed by cutting so the S/A will fit in a waste can. Blankets, as opposed to drivers, need not be completely disassembled for storage in RSWF (this is due to the much lower decay power of blankets with respect to driver fuel);
- Load a storage waste can, known as the HFEF-5 cask, with six blanket S/As or the elements from two drivers;
- Section S/A hardware and load nine sets of hardware into another waste can;
- Load the inner can into an outer can, insert the shield plug, and weld shut;
- Transfer the HFEF-5 cask to RSWF, and unload;
- Return the cask to the HFEF truck-lock, and prepare for another shipment.

III. ESTIMATION OF THE SYSTEM'S PARAMETERS

To obtain a fair estimate of the operational times for performing different modes of fuel handling in the EBR-II building, the fuel handling log-book for June 93-April 94 and the stored data on all fuel loading/unloading activities in the Data Acquisition System (DAS) for January 94-April 94 were analyzed and statistical tools were used to determine the best fit probability distribution. In some cases, modifications to the existing systems or practices are planned, but not yet incorporated. In those cases, best estimates of required times were made. The same information was used to estimate Mean Time Between Failures (MTBF) and Mean Time to Repair

Table 1. Overall Storage Time (since birth) at HFEF

Type of S/A	Cooled Pits (Days)	Uncooled Racks (Days)
Driver	51±15	266±79
Half-worth driver	12±2.5	58.5±14
Control rod	29.5±3.5	146±14
Blanket	0	1.6±1

(MTTR) of different components of the fuel handling equipment. All modelling assumptions were discussed with the staff and consensus was achieved. Table 2 shows the results of the statistical analysis of Modes 1-4 fuel handling within the EBR-II reactor building. In a similar manner, the times and statistical distributions for operations at the IBC wash station and HFEF were obtained.

IV. MODELLING OF THE FUEL HANDLING SYSTEM

After compiling the statistics on the fuel handling process, the authors studied the feasibility of using different approaches to model the situation. Upon careful evaluation of alternatives, it was recognized that the complexity of fuel handling systems and the statistical nature of times to perform operations precluded the use of a deterministic model because it could not depict the actual performance of the system over time. Therefore, it was decided to use one of the commercial simulation packages to simulate the fuel handling process at ANL-W.

Use of simulation modelling as a tool to address complex systems enables the modeler to measure the performance of the existing or proposed systems under different operating schemes. It can help management make basic evaluations of the different options. Therefore, simulation of the system's operation has rapidly become one of the most useful and common applications of computers. Simulation can be used 1) as an explanatory device to define a system; 2) as an analysis vehicle to determine critical issues; 3) as design evaluator to synthesize and evaluate proposed solutions, and 4) as predictor to forecast and aid in planning future.

In the simulation model developed for fuel transfers at ANL-W, different scenarios were studied in which the number and the availability of different resources such as the IBC (normally there are two IBC's for use, but extended outages of one had to be studied based on past experience), the operating hours of different crews and the fuel handling operational procedures were varied. Comparing the resulting number of transferred subassemblies in two years of simulation time, the authors were able to determine a few optimal policies that will help ensure that the fuel unloading schedule can be met.

The specific scenarios that were modelled are: (1) One IBC versus two; (2) the IBC crew working one 8 hour shift, one 12 hour shift, or two 8 hour shifts; and (3) the VAD crew in HFEF working one 8 hour shift or one 12 hour shift.

The results of the simulation for two years of transfers using seven different operation scenarios (permutations of the above scenarios) are shown in Table 3. Comparison of the results of different operating scenarios, as depicted in Table 3, reveals some definite critical items that must be in place to meet the required schedule. The results are discussed below.

1) Comparison of the number of S/As

Table 2. Statistical Summary for Fuel Handling

Mode of Fuel Handling	# of data points	Mean (min.)	Standard Deviation	Min. Value	Max. Value	Best Fitted Distribution
Mode 1						
Preparation Time	23	110	142	5	512	Exponential (mean=90)
Aux. to FUM Time	22	57	70	8	245	Exponential (mean=45)
FUM to Basket Time	23	118	103	23	489	Exponential (mean=135)
Total # Time	25	275	183	76	644	Normal (mean=245,S.D.=180)
Mode 2						
Total Time	18	38	14	11	76	Normal (mean=37, S.D.=14)
Mode 3						
Preparation Time	7	251	309	44	933	Exponential (mean=225)
Core to Basket Time	18	38	20	12	78	Normal (mean=38, S.D.=19)
Total Time	18	136	220	12	936	Exponential (mean=85)
Mode 4						
Preparation Time	16	40	46	5	190	Exponential (mean=35)
Basket to FUM Time	24	50	26	6	98	Uniform (between 0 and 100)
FUM to IBC Time	28	33	22	4	81	Normal (mean=29, S.D.=22)
IBC to FCF Time	29	188	136	25	554	Normal(mean=170, S.D.=134)
Total Time	29	107	53	40	313	Normal (mean=100, S.D.=52)

transferred to HFEF for the first and the second year (the N1 column in Table 3) shows no significant differencefrom the first year to the second year, whereas comparison of the number of S/As processed at HFEF (the N2 column) shows a significant difference. The reduction in S/As processed in HFEF in the second year is due to the assumptions of the starting inventory in HFEF cooled pits and air storage racks at the beginning of year 1. This gives a backlog of S/As for HFEF to process at an accelerated rate for the first year. When they are depleted, HFEF is depending on transfers from EBR-II for S/As to process; thus the overall rate becomes dictated by EBR-II's transfer rate.

2) Increasing the number of IBCs has a direct effect on increasing the system's performance. This is clearly seen by comparing any two rows in Table 4 in which the number of IBC's is increased from one to tow. For instance, comparison of the first and second rows shows an increase of transfers from EBR-II from 61 to 109 for the first year, or a 60% increase. Comparison of rows 3 and 4 shows almost a 100% increase through the use of tow IBC's. This demonstrates quantitatively the absolute necessity of having two IBC's available during the fuel unloading process.

3) With all else being equal, increasing the operating hours of the IBC crew (crew 1 in Table 3) has a direct effect on the performance of the system. Comparison of rows 1 and 3 shows a 50% increase in transfer rate by increasing the IBC crew's hours from 8 hours to 12 hours, even with one IBC. With two IBC's, the rate is increased almost 75% (rows 2 versus 4).

4) Increasing the operating hours of the VAD crew (crew 2 in Table 3) without increasing the operating hours of the IBC crew has no significant impact on the performance of the system. This is seen by comparison of rows 2 and 5 in Table 3. It can be shown that for an optimum fuel handling rate, the IBC crew should operate more hours than the VAD crew.

IV. CONCLUSIONS

Simulation of the fuel handling system in any nuclear power plant is an important part of

Table 3. Results of Two Years' Simulation of the System

Y	Scenario			No. of S/A Processed		No. of Cans Shipped		
	IBC	Crew 1	Crew 2	N1	N2	C1	C2	C3
1	1	8	8	61	101	16	11	27
	2	8	8	109	144	24	14	38
	1	12	8	95	131	21	14	35
	2	12	8	177	197	32	21	53
	2	8	12	112	142	23	13	38
	2	12	12	180	202	32	22	55
	2	16	12	210	224	37	24	61
2	1	8	8	65	64	11	7	18
	2	8	8	115	112	18	14	32
	1	12	8	93	93	16	10	26
	2	12	8	186	186	31	21	52
	2	8	12	114	117	20	13	33
	2	12	12	188	186	31	21	52
	2	16	12	219	220	36	25	61

IBC= The number of IBC casks available (there are a maximum of two)
Crew 1= The IBC crew, or cask handling crew
Crew 2= The VAD crew in HFEF
N1 =The total number of transferred S/As from the EBR-II to the HFEF cooled pits
N2 =The number of S/As that were processed at the HFEF and shipped to RSWF
C1 =The number of cans filled with blanket S/As and shipped to RSWF
C2 =The number of cans filled with hardware and shipped to RSWF or RWMC
C3 =The total number of cans that were shipped out

radioactive waste management. Lack of availablemodels has forced the facilities to exploit deterministic models or personal judgement to estimate the required time to unload a nuclear reactor and to dispose of the radioactive waste materials. The experience with utilizing simulation techniques described in this paper have demonstrated the usefulness of these methods. There are many other sites in the DOE complex that have similar complexities in the path to storage or processing. With the current emphasis on waste management and the cost associated with depleted fuel disposal, investigation into the behavior of the fuel handling system under different operating scenarios should be beneficial to all. The techniques described in this paper can easily be generalized to other facilities or processes.

REFERENCES

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