RELIABILITY AND AVAILABILITY EVALUATIONS OF WASTE REPOSITORY SYSTEMS AND MECHANICAL EQUIPMENT+

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INTRODUCTION

As part of the program for development of repository equipment, the Office of Nuclear Waste Isolation (ONWI) initiated a Reliability, Availability, and Maintainability (RAM) analysis program. The initial step in the ONWI RAM program was the development of qualitative and quantitative methodology that could be used by designers and program managers, as well as RAM specialists, to determine and fulfill the availability and maintainability requirements of repository equipment. The recommended methodology has been assembled in a Guidebook[1] that provides (a) an overview and management perspective for a RAM program and (b) detailed step-by-step instructions on when and how to apply the methodology. This paper briefly describes the methodology that was developed and presents insights gained from application of the methodology to representative repository equipment.

METHODOLOGY

Availability is one index of reliability for repairable systems or devices and may be defined as the proportion of time, in the long run, that it is in, or ready for service. Quantitatively, this is stated as

$$\text{Availability} = \frac{\text{Uptime}}{\text{Total Time}} = \frac{\text{MTBF}}{\text{MTBF + MTTR}} \qquad (1)$$

where

MTBF = Mean Time Between Failures
MTTR = Mean Time To Restore (Repair)

RAM analysis is concerned with evaluating ways for improving system availability by increasing MTBF or reducing MTTR.

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A wide range of RAM techniques have application to repository equipment and configuration development. The techniques vary from simple qualitative reviews to complex, quantitative techniques. Quantitative RAM analyses are closely related to the techniques used in probabilistic risk assessment (PRA). Both RAM and PRA deal with the tasks of quantifying the expected frequencies of undesired events and in quantifying the consequences of such events. The consequences of interest in RAM are system downtime or loss of production. Unlike requirements for mitigation of safety related consequences, the requirements for mitigation of low availability are generally constrained by cost-benefit considerations. Both the level of effort devoted to RAM evaluations and the amount of program resources applied to developing or operating the system for improved availability must be commensurate with the expected gain in availability. Figure 1 summarizes the types of methodology recommended for application to repository development.

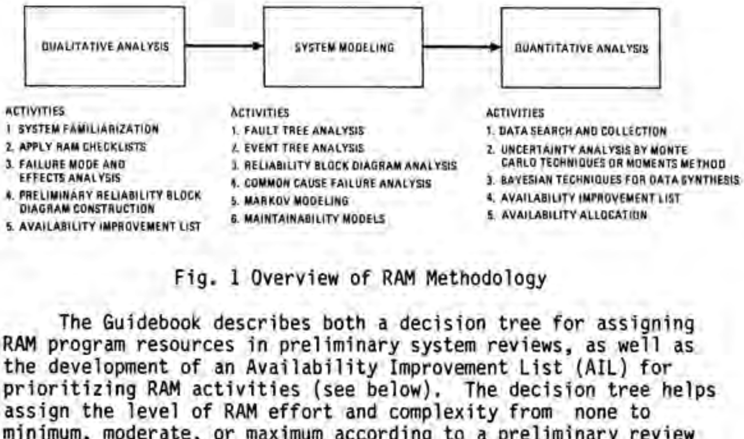

Fig. 1 Overview of RAM Methodology

The Guidebook describes both a decision tree for assigning RAM program resources in preliminary system reviews, as well as the development of an Availability Improvement List (AIL) for prioritizing RAM activities (see below). The decision tree helps assign the level of RAM effort and complexity from none to minimum, moderate, or maximum according to a preliminary review of the significance of the particular item with respect to a) repository throughput, b) accessibility during operation, c) level of RAM experience of the item, and d) level of confidence in knowledge of a,b, and c.

Unless designers have an extremely high level of experience and confidence that an item will be adequately reliable, the recommended minimum for all repository equipment is that designers apply reliability and maintainability checklists to develop an awareness of considerations of design, maintenance and human factors that can improve reliability and maintainability. Detailed Reliability and Maintainability checklists are provided in Appendix E of the Guidebook.

The use of qualitative failure modes and effects analyses, reliability block diagrams, and elementary fault trees by design personnel is encouraged. Designers,aided by others familiar with the performance history of typical equipment, contribute to priortizing equipment with respect to the need for availability improvement effort. The formalization of this process is called an Availability Improvement List (AIL) in which each item receives an Availability Improvement Ranking (AIR).

It is recommended that the more complex quantitative analyses be performed by RAM specialists with review by others. Such analyses include quantitative reliability and maintainability predictions, fault tree/event tree evaluation, common-mode failure evaluation, lag/surge storage analyses , configurations and equipment trade-offs, data handling, and uncertainty analysis.

A fundamental concept for the RAM program is that some quantitative availability goal is established for the total repository system. The overall repository availability goal is apportioned or "allocated" to various systems, subsystems and equipment to produce numerical availability goals successively at each level of assembly. The process of allocating goals proceeds to a level of assembly where feasibility of achievement can be assessed. This is usually the point at which statistical values on MTBF (Mean Time Between Failures) and MTTR (Mean Time To Repair) are known or amenable to estimation. By performing this process early in the program, management can assess the basic feasibility of achieving the overall repository or equipment goals. The AIR ranking is updated as quantitative analyses reveal discrepancies between what is allocated and what appears achievable by prediction . System improvements are considered that will reduce or eliminate such discrepancies. Such improvements may include use of components or system concepts having higher inherent reliability or maintainability, use of redundant components to improve system reliability, or providing lag or surge storage capacity at certain points in the flow stream. Results of these analysis and cost trade- offs are fed back to the designers. Through this process, the design is brought into compliance with the goals, if cost-effective. Availability goals, if infeasable or not cost-effective, would be reallocated.

To perform quantitative RAM analyses, MTBF and MTTR data are needed. Although there is sometimes a paucity of such data for equipment of interest, the Guidebook describes methods for establishing these parameters and the uncertainty distributions for situations of statistically meaningful data as well as scarce data. The use of Bayes' Therom is one means to generate uncertainty distributions for the RAM data, using a computer code called BROLS[1].

While point estimates of reliability and availability based on point estimates of MTBF and MTTR are used as approximate indications of the relative contributions of various subsystems to repository performance or of the relative merits of alternative systems, it is important to recognize and explicitly deal with the effects of uncertainties in the data. The STADIC Code[1] is used to combine data uncertainty distributions in complex availability expressions to produce the net probability distribution for the system or subsystem availability factor.

APPLICATIONS TO REPRESENTATIVE EQUIPMENT

To illustrate the techniques, analyses were performed on selected portions of a reference repository design. The Conceptual Reference Repository Design (CRRD)[2] was developed for ONWI as a composite design of two other conceptual repositories and a spent fuel packaging facility. The CRRD includes unloading of shipping casks and transfer of the bare fuel assemblies under water (lag storage pool and canal system) until they are brought into a canister loading and sealing facility (weld and test cells). Many of the example applications used the lag storage pool area. It includes cranes, pool canal isolation gates, a motorized basket transfer buggy, pool water cleanup and supply system, building HVAC and supporting power supplies. The results of application of RAM methodology to the CCRD are described below.

The applications illustrate the range of methodologies from qualitative, designer-oriented faiure mode and effect analysis (FMEA) to RAM-specialist-oriented uncertainty analysis. It demonstrates how each level may be used independently or in conjunction with others to produce the desired level of RAM effort.

Allocation

The use of "top-down" allocation technique is illustrated for the CRRD[1]. For purposes of allocation, the CRRD high-level waste (HLW) handling system was represented as a series string of 15 subsystems .

The basic idea of availability allocation for an equivalent series system is that the overall system availability (A_S) is the product of the effective availabilities of the subsystems (A_i)in the string, and the system unavailability (U_s)is approximately equal to the sum of subsystem unavailabilities (U_i):

$$\begin{aligned} A_S &= A_1 \times A_2 \times \ldots A_n \\ U_S &= 1 - A_S \cong U_1 + U_2 \ldots U_n \end{aligned} \qquad (2)$$

where $U_i = 1 - A_i$ for each subysstem.

In allocation, an overall goal is set for the top level of assembly. For example, a goal of 80% availability (U_S=0.2) was set for the HLW system. The subgoals for A_1, A_2, etc. are allocated according to weighting factors that are derived from their expected relative Mean Time Between Failure (MTBF) and relative Mean Time to Restore (MTTR). An algorithm detailed in the Guidebook and based on work by MTI[3], uses relative MTBF and MTTR scoring by cognizant individuals to develop the allocation weights. Relative MTBF weighting among subsystems or equipment is based on four attributes: system complexity, state-of-art, performance time, and environmental conditions. Similarly, the relative MTTR weighting is developed from scores on preparation time, verification time, fault location time, spare procurement time, repair time and checkout time. Generic weights of importance are applied to each attribute. Special forms are provided in the Guidebook to develop the MTBF and MTTR scoring. The scores are processed by the ALOCAT Code which produces the availability and unavailability factors allocated to each subsystem for a given input goal for the top level. For example, to achieve 80% availabiity for the HLW handling system, the subgoal allocated to the Lag Storage Pool was A=0.984 (U=0.016).

To illustrate further, the allocation was carried down to the equipment in the lag and presentation pool area. The unavailability goal of 0.016, from above, was input to ALOCAT along with relative MTBF and MTTR scores for this equipment. The results are shown in Table I.

TABLE I

ALLOCATION OF UNAVAILABILITY TO LAG STORAGE POOL SYSTEM

ID	SYSTEM NAME		ALLOWED UNAVAILABILITY FACTOR	
		SYSTEM GOAL : SUBSYSTEM GOAL :	A=0.9, U=0.1 U_5=7.8(-3)	A=0.8, U=0.2 U_5= 1.6(-2)
5-1	POOL GATES		1.1(-3)*	2.2(-3)*
5-2	GANTRY CRANES		1.4(-3)	2.9(-3)
5-3	MAINTENANCE CRANE		6.5(-4)	1.4(-3)
5-4	WATER COOLING/TREATMENT		1.3(-3)	2.8(-3)
5-5	INSTRUMENTATION		1.5(-3)	3.1(-3)
5-6	MOTORIZED TRANSFER BUGGY		1.9(-3)	4.1(-3)
		TOTAL:	7.8(-3)	1.6(-2)

*( ) INDICATES POWER OF 10

The U's thus derived give an early indication of whether there are any areas that are problematical and of need of special RAM consideration, such as adding redundancy, providing modular maintenance, etc. in order to meet its alloction. For perspective, consider that most repairs would take between one day (MTTR 24 hours) and a month (MTTR 720 hours). To achieve a U on the order of .004, the allowable MTBFs would be 0.7 year and 21 years respectively. Clearly, the latter would be difficult to achieve for typical mechanical equipment and would require special consideration.

Development of an Availabilty Improvement List (AIL)

An Availability Improvement List is a list in which some of the subsystems, equipment items or components are ranked according to their influence on the HLW system unavailability and the uncertainty of knowledge about their influence. Only those items with either the largest effect on system unavailabiity and/or the largest uncertainty are put on the list. The ranking is achieved by a simple, numerical formula called an AIR (Availability Improvement Ranking).

Development of an AIL begins after a Failure Modes and Effects Analysis (FMEA) has been performed, in which frequency and consequences of defined failures are assigned numerical importance factors. An FMEA is a well-known method for performing qualitative and, sometimes quantitative reliability evalution in a methodical fashion. For the Guidebook, the recommended FMEA worksheets also include one column labeled "failure frequency category" and two "result" columns labeled "C" and "T". The latter correspond to effects on capacity ("C") or throughput rate reduction and time ("T") or duration of an outage. These columns are used for numerical importance factors corresponding to the schedule defined in Table II.

TABLE II

FMEA AND AIR/AIL NUMERICAL FACTORS

FMEA - FACTORS	DEFINITIONS FOR FMEA FACTORS	AIR/AIL FACTOR
FAILURE FREQUENCY CATEGORIES:		"F"
1	AN EXTREMELY LOW PROBABILITY FAILURE THAT IS NOT EXPECTED TO OCCUR DURING THE OPERATING LIFETIME OF THE REPOSITORY ($\lambda < 10^{-6}$/HR)*	0.1
2	A LOW PROBABILITY FAILURE WHICH WOULD BE EXPECTED TO OCCUR A FEW TIMES DURING THE PLANT LIFETIME (10^{-6}/HR < λ < 10^{-4}/HR)	1.0
3	A FAILURE WHICH WOULD BE EXPECTED APPROXIMATELY YEARLY (10^{-4}< λ < 10^{-4}/HR)	10.0
4	A FREQUENT FAILURE WHICH RESULTS FROM DAY-TO-DAY OPERATION AND WOULD BE EXPECTED TO OCCUR SEVERAL TIMES PER YEAR ($\lambda > 10^{-3}$/HR)	100.0
RESULT NUMBERS: TYPE C	(AFFECTING THROUGHPUT FACTOR)	"D"
1	FAILURE WILL HALT ALL WASTE EMPLACEMENT	1.0
2	MAJOR DEGREDATION OF THROUGHPUT (70- 90% REDUCTION)*	0.8
3	MODERATE DEGRADATION OF THROUGHPUT (40-70% REDUCTION)	0.5
4	MINOR DEGRADATION OF THROUGHPUT (10-40% REDUCTION)	0.3
5	NEGLIGIBLE DEGRADATION OF THROUGHPUT (< 10% REDUCTION)	0.1
TYPE T	(AFFECTING TIME DURATION OF THROUGHPUT REDUCTION)	"E"
1	CATASTROPHIC FAILURE (SITE PERMANENTLY CLOSED)	500
2	MAJOR INTERRUPTION OF BURIAL PROCESS (λ> 6 WEEKS)*	50
3	MODERATE INTERRUPTION OF BURIAL PROCESS (1 WEEK< τ < 6 WEEKS)	25
4	MINOR INTERRUPTION OF BURIAL PROCESS (1 DAY< τ<1 WEEK)	5
5	NEGLIGIBLE INTERRUPTION OF BURIAL PROCESS (τ < 1 DAY)	1

* THE NUMERICAL RANGES CITED ARE SUBJECT TO REDEFINITION BY RAM PROGRAM MANAGEMENT

The C and T values are assigned by cognizant analysts and designers and used in developing AIR values and the AIL. An AIR is derived for every item in the FMEA as the product of four factors:

$$AIR = F \times O \times E \times S. \qquad (3)$$

Numerical values for F, O, and E are assigned as shown in Table II. The S relates to the analyst's uncertainty about values assigned for F, O, and E and is assigned a value of 1,3,5,7, or 10. To be placed on the AIL, the item's AIR should exceed 10.

Items having AIR less than 10 should receive minimum RAM effort. AIRs between 10 and 40 have either availability concerns or large uncertainty and should be subject to a moderate RAM effort. AIRs greater than 100 probably have a combination of several availability concerns (e.g. both high frequency of repair and long repair time or large uncertainty). Those items should receive maximum RAM effort. Steps for executing minimum, moderate and maximum RAM efforts are detailed in the Guidebook.

Figure 2 shows the AIL developed for the Lag Storage and Pool System of the CRRD as an illustrative example. This example reflects the opinion or perceptions of the Guidebook authors and does not necessarily represent the results that would be obtained by a thorough application aided by CRRD designers. Continuing with the illustration, however, the AIL clearly indicates two subsystems having large AIRs for which the maximum RAM evaluation effort is recommended. Hence, the transfer buggy and canal gates were selected as topics to illustrate several of the quantitative analytical methods presented in the Guidebook. Some of these are discussed below.

AVAILABILITY IMPROVEMENT LIST (AIL)
FOR SPENT FUEL LAG STORAGE AND
PRESENTATION POOL SYSTEM (**)

SYSTEM OR PROCESS				NAME: SPENT FUEL LAG STORAGE AND PRESENTATION POOL SYSTEM FUNCTION: TRANSFER SPENT FUEL BASKET TO DRYING STATION, STORE FUEL ASSEMBLIES WHEN REQUIRED		ID NUMBER: 2.5 SHEET 1 OF 1	
PREPARED BY: M.V. FRANK		DATE: 1986					
ITEM NO. FROM FMEA	SUBSYSTEM ASSEMBLY, COMPONENT OR PROCESS		AIR	DESCRIBE BASIS FOR RANKING	DESCRIBE PROPOSED CORRECTIVE ACTION	STATUS*	EFFORT+
	NUMBER	NAME					
5	NA	SELF-PROPELLED TRANSFER BUGGY	275	HIGH UNCERTAINTY FOR ESTIMATED FAILURE RATE OF NOT DESIGNED EQUIPMENT. FAILURE OF THIS ITEM CAUSES PROCESS INTERRUPTION	DESIGN FOR HIGH AVAILABILITY, PUT HIGH PRIORITY ON DESIGNING THIS ITEM.	I	MAX
3	NA	ISOLATION GATES NEAR PRESENTATION POOL	182	RELATIVELY HIGH UNCERTAINTY FOR ESTIMATED FAILURE RATE OF NOT DESIGNED EQUIPMENT. FAILURE TO OPEN MAY BE DIFFICULT TO REPAIR AND MAY INTERRUPT EMPLACEMENT PROCESS	PROCEED WITH DESIGN	I	MAX
10	NA	OFFSITE POWER SYSTEMS	36	OFFSITE POWER FAILURES MAY CAUSE LENGTHY OUTAGES	DESIGN REDUNDANT AND SEPARATE OFF-SITE POWER PATHS	I	MOD
7	NA	POOL DECONTAMINATION AND COOLING SYSTEM	45	RELATIVELY HIGH FAILURE RATE FOR SYSTEMS WHICH RELY ON ELECTRIC PUMPS	NATURAL CONVECTION BACK-UP COOLING MAY REDUCE FAILURE RATE	I	MOD
8	NA	HVAC FOR LAG STORAGE AREA	30	RELATIVELY HIGH FAILURE RATE FOR ELECTRIC COMPRESSOR/FAN SYSTEMS. PERSONNEL EVALUATION WOULD SHUTDOWN PROCESS		I	MOD
2	NA	ISOLATION GATES NEAR LAG STORAGE POOLS	18	RELATIVELY HIGH CERTAINTY FOR ESTIMATED FAILURE RATE OF NOT DESIGNED EQUIPMENT	PROCEED WITH DESIGN	I	MOD

*I : ITEM IDENTIFIED
A : URGENT ACTION REQUIRED
P : SOLUTION PROPOSED
C : CORRECTION COMPLETE
E : ITEM NEEDS MORE EVALUATION BEFORE PREPARING SOLUTION

** THE DEVELOPMENT OF THE EXAMPLE AIL IS FOR ILLUSTRATION PURPOSES ONLY AND SHOULD NOT BE INTERPRETED AS ACTUAL RECOMMENDATIONS FOR THE MRTS PROGRAM.

+MAX: MAXIMUM AVAILABILITY IMPROVEMENT EFFORT REQUIRED.
MOD: MODERATE AVAILABILITY IMPROVEMENT EFFORT REQUIRED

DESIGN ACTIVITIES FOR EACH LEVEL OF EFFORT DEFINED IN FIGURES 5-2 AND 5-3 (REF. 1)

Fig. 2 Availability Improvement List for Lag Storage Pool Area

Quantitative Fault Tree Analysis

One of the techniques that may be required in "maximum" RAM efforts is fault tree analysis (FTA). FTA is a widely recognized method of logical deduction to predict the probability of some "top event" that is significant to system reliability, availability or safety analysis by combining the probabilities of more basic events. The tree construction is continued downward in level of assembly until a level is reached where representative data on failure frequency (or probability) and repair time can be determined.

An example of a fault tree is shown in Fig. 3 for the self-propelled canal buggy. The final expression for buggy unavailability, derived from the fault tree is:

$$U_B = Q_1R_1\tau_1 + \lambda_2\tau_2 + Q_3R_3\tau_3 + \lambda_4\tau_4 + \lambda_5\tau_5 + \lambda_6\tau_6 + \lambda_7\tau_7 + \lambda_8\tau_8 + \lambda_9\tau_9 \qquad (4)$$

where λ_i = frequency of basic event i (per hour)

τ_i = duration of event i (hours)

Q_i = demand failure probability of basic event (per demand)

R_i = demand rate for event i (per hour)

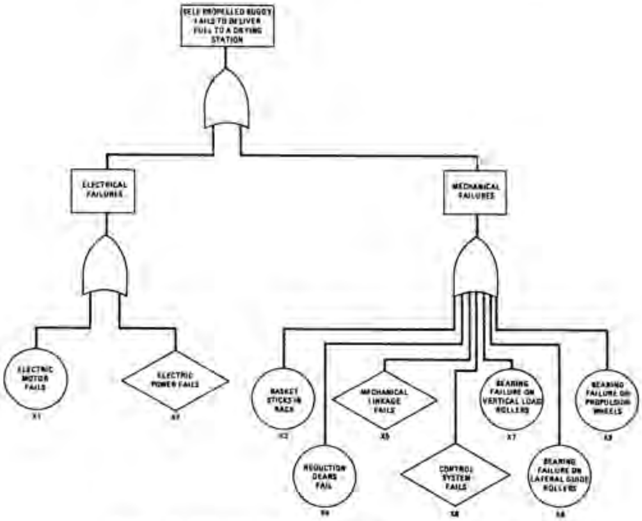

Fig. 3 Fault Tree for Self-Propelled Buggy

The expression was evaluated using generic failure rate and repair time data for several sources and demand frequency derived from the CRRD[2]. A sample of this data is shown in Table III This table also shows the uncertainty factors around the median values of λ and τ for assumed log-normal probability distributions. When the median values are entered into Eq.4 the point estimate for U_B is 0.0125. This corresponds to about 4 months of downtime over the 30 year active lifetime of the reference repository. Note that this value exceeds the 0.0041 example allocation for the buggy in Table III.

TABLE III

REPRESENTATIVE INPUT DATA TO BUGGY FAULT TREE

SYMBOL	DESCRIPTION	MEDIAN	UNCERTAINTY FACTOR *
R_1	DEMAND RATE FOR ELECTRIC MOTOR (8 DEMANDS/ 8 HR = 1/HR)	-	-
τ_1	REPAIR TIME FOR ELECTRIC MOTOR	40 HRS	10
Q_1	FAILURE PROBABILITY OF ELECTRIC MOTOR TO START	3×10^{-4}/ DEMAND	3
λ_2	FAILURE RATE OF ELECTRIC POWER	4.7×10^{-7}/HR	4.5
τ_2	REPAIR TIME FOR TRANSFORMERS	200 HRS	25
λ_4	FAILURE RATE OF REDUCTION GEARS	1.5×10^{-5}/HR	1.3
τ_4	REPAIR TIME FOR REDUCTION GEARS	48 HRS	2
λ_5	FAILURE RATE OF MECHANICAL LINKAGE	3×10^{-7}/HR	3
τ_5	REPAIR TIME FOR MECHANICAL LINKAGE	10 HRS	1.7

* 95% CONFIDENCE LIMIT FOR LOG-NORMAL DISTRIBUTION

To bring the expected buggy unavailabilty into line with the allocation some improvement in component or system reliability might be tried. For example, a redundant motor might be provided to a given buggy or a complete, redundant buggy might be employed. Either action would bring the medium availability to about 10^{-4}.

It is interesting to note, however, the effect of propagating data variability in the analysis for system unavailability. The expression for U_B, Eq. 4 was evaluated with the STADIC-II code[1] which uses a Monte Carlo process to sample values of λ and τ from their repeative frequency distributions and to insert these in the analytic expression. The result is displayed as the complimentary cumulative distribution function (CCDF) for buggy unavailability shown in Fig. 4 which shows the probability of exceeding a given value of U_B.

From this figure, it is seen that the median value (where the probability =0.5)is about 0.014 and agrees quite well with the point estimate from hand calculation described above. However, this means that there is a 0.5 chance of exceeding this value. Furthermore, the right hand tail of the CCDF indicates that there is about 10% chance that U_B will even exceed 10^{-1}. Hence, if uncertainty in data cannot be reduced, some means must be found to lower the expected value considerably and thereby shift the curve to the left in order to meet the allocation with high confidence.

STADIC-II could be used to combine the uncertainty distributions for the unavailability of all repository subsystems to obtain the CCDF of the net unavailability of the repository. The probability of exceding a given repository availability goal would be readily evident.

Surge/Lag Storage Analysis

The effective availabilty of a stage of a process or of an entire string of subsystems can be improved by strategic use of lag/surge storage. Fundamentally, a storage volume allows a degree of decoupling of portions of the series string of subsystems. Should a subsystem upstream of storage fail, the downstream process and waste emplacement process could continue by taking waste packages out of the storage while upstream facilities are repaired. So long as the effective drainage time for the storage exceeds the MTTR of the upstream portion , the effective availability of the upstream system is unity. To be effective, however, the storage volume must be refilled in a time in which short compared with the effective MTBF of the upstream system. Similar considerations apply for failures downstream of the storage volume, which could continue accepting waste shipments from upstream as long as there is empty space in the storage volume.

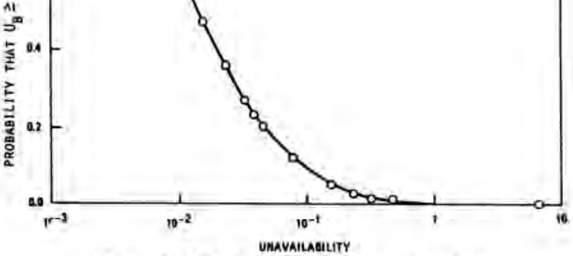

Fig. 4 CCDF for Buggy Unavailability

To analyze the effect of lag/surge storage on system availability, a Markov model was used to develop the effective availability of a series of subsystems having standby redundant active subsystems as well as a surge storage volume, as depicted in Fig. 5.

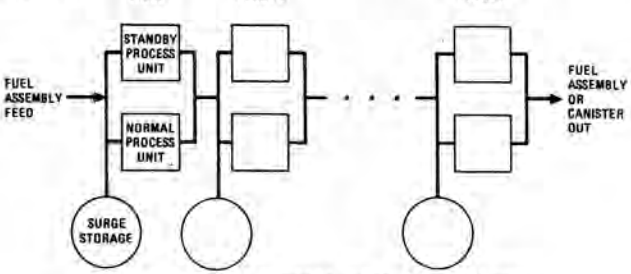

Fig. 5 RBD for Process with Surge Storage

The system availabilty is the product of the stage availabilities. The availability for the jth stage is

$$A_j = (1 + F_j)^{-1} \qquad (5)$$

where F_j is an expression for the ratio of effective MTTR to effective MTBF. The effective MTBF accounts for the presence of the standby unit and includes a factor for the failure to start of the standby unit. The effective MTTR includes a reduction factor that corresponds to the volume of the storage in terms of T_j, the time-to-empty at full demand rate. The effective MTTR also includes a term that corresponds to the time to refill the storage volume and is proportional to the excess capacity in the system. The excess capacity factor is called k and is the ratio of total throughput capacity of stage j to the demand capacity.

Using parameters representative of repository equipment (MTBF= 1000 hrs, MTTR =20 hrs, and 10^{-3} failures per demand for the standby unit) the expression was evaluated for various k factors and surge empty time (T_j). The expression was also evaluated for a system with no standby. The results are shown in Fig. 6.

For k=1 (no excess capacity), in which the volume cannot be refilled while the system maintains normal throughput, the surge volume doen't provide any availability improvement. However, any $k > 1$ yields a benefit from the storage volume in reducing stage unavailability as shown by the curves for k=1.25, 1.5, 2, and 4.

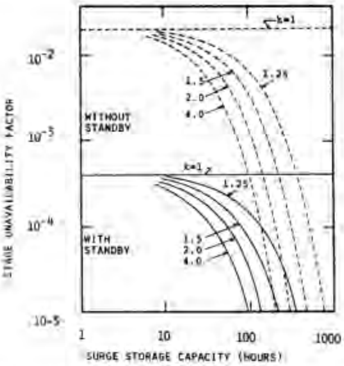

Fig. 6 Stage Unavailability with Storage

To gain a full order of magnitude in unavailability, with or without a standby process unit, requires storage volume on the order of 100 hours for k=2. It is seen that increasing k beyond 2 is not very effective in providing additional reductions in effective stage unavailabiity. Note, however, that adding only a standby unit (i.e. comparing the two k=1 cases) is as effective as adding 100 to 600 hours of storage time to a stage without standby.

The use of lag/surge storage may be an effective alterative to providing redundant active process units to a stage, especially if the storage volume is just an inexpensive passive element. The basic availability of the active element without standby is 1.9×10^{-2}, which is similar to the median value for canal buggy unavailability, U_B, described above. Hence, instead of using redundancy to reduce U_B to 10^{-4}, a surge storage of 100 hours or more would approach the allocated target of U_B of 10^{-3}. For storage of waste packages, however, the lag/surge volume may require active cooling systems. While the failure of this cooling system may not seriously affect the net availability of the process stream, the net cost of the storage system might exceed that of a redundant motor or canal buggy system.

CONCLUSIONS

The equipment and processes that are developed for application in a nuclear waste repository should be subjected to a reliabiity, availability, and maintainability program to better assure that the repository can accept and process the required amount of waste over its intended operational lifetime. A methodology for developing and conducting such a RAM program has been assembled in a Guidebook that provides for both qualitative and quantitative analysis techniques for identifying and evaluating potential problems, stating their effects, and suggesting alternative corrective actions.

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