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Consolidated Fuel Reprocessing Program

THE INFLUENCE OF MAINTENANCE SYSTEM RELIABILITY AND MAINTAINABILITY CHARACTERISTICS ON OVERALL PLANT AVAILABILITY*

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NOTICE

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†Operated by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy.

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Key Words: System Availability, Markov Analysis, Modeling, Maintenance Deferral

Summary and Conclusions

Performance goals for complex processes are often linked with achieving high availability of plant equipment. This requires that maintenance systems, which sometimes include complex electromechanical equipment operating in a hostile environment, meet certain requirements for reliability and maintainability. This paper develops several Markov probability models to evaluate the impact of maintenance system availability on the overall plant. The models considered included the case when the maintenance equipment is itself under repair when a failure occurs on process equipment. Examination was also given to the situation where the maintenance equipment is operated in a degraded condition (i.e., longer times are required to complete repairs).

The results of the analysis identified conditions under which failures in the maintenance system could have a significant adverse effect on plant availability. Maintenance system failures affect the average times required for process repairs, which can affect the availability of each process subsystem in the plant. A useful simple rule for incorporating effects of maintenance system failures into plant availability estimates is to multiply repair rates corresponding to ideal conditions (no maintenance

failures) by the expected availability of the maintenance system. This rule applies when the maintenance system is available on a standby status when a process failure occurs. The effect is somewhat greater when the maintenance equipment is subject to interim breakdowns, between process failures. The analysis also indicated conditions under which overall plant availability could benefit by permitting some degradation in maintenance equipment capabilities, before repairing this equipment with a backup system. As a rough rule, the degradation should not increase average repair times by more than about a factor of two.

1. INTRODUCTION

It is typically assumed in plant availability analyses that the maintenance system is available for repairs whenever called upon by plant equipment. However, maintenance systems are sometimes themselves electro-mechanically complex and are subject to breakdowns. Maintenance system failures can significantly affect overall plant availability because the performance of the maintenance system influences the availability of each equipment system. There is a general need to develop plant design guidelines in which the relations between performance characteristics of the maintenance system and plant equipment systems are taken into account.

This work was conducted as part of the development of a nuclear fuel reprocessing plant design in which plant equipment operates in a hostile, high radiation field environment. Because of the hostile environment, the equipment in the plant must be maintained remotely by robot-like, electro-mechanical servomanipulators (EMSs). Typically, maintenance systems are composed of two parts: The primary system and another backup system to repair the primary system should it fail. When not repairing the primary system, the backup maintenance system may also be used for maintenance work on plant equipment. A question of considerable practical interest concerns not only the characteristics of the primary maintenance system, but also the backup maintenance equipment needed to operate the plant. This work was supported as part of a joint collaboration program between the U.S. Department of Energy and the Power Reactor and Nuclear Fuel Development Corporation of Japan.

2. ELEMENTARY MODEL FOR PROCESS AVAILABILITY

An elementary probability model for operation of a subsystem subject to breakdowns postulates a sequence of run-until-failure, shutdown-to-repair intervals. This model leads to the following formula for the intrinsic availability A or steady-state probability that the subsystem is in the operating mode (Ref 1):

$$A = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} , \tag{1}$$

where MTBF designates mean operating time between failures requiring shutdown, and MTTR designates mean down time to repair. The formula does not consider minor failures which may degrade operations and which may be postponed for repairs until the next scheduled shutdown. In general, both the operating time between failures and the down time for repairs will be random variables. The above formula can be shown to apply, regardless of the nature of the probability distributions from which these random variables are drawn, provided that the completion of each repair constitutes a renewal (i.e., the system is restored such that the next failure-repair cycle begins with essentially the same initial conditions as the previous failure-repair cycle). The renewal model provides only an approximation for situations where there is gradual degradation in equipment performance over time; however, it provides useful insight into system effects of random failures during periods between scheduled shutdowns for preventative maintenance.

A specific example of a renewal process is the case in which the probability of a failure occurring in the next small interval of time (given that the equipment is operating at the beginning of the interval) is a constant, independent of operating time. As shown in ref. 1, this leads to exponential probability distributions for the operating time between successive failures. The same type of assumption is often made for repair times in reliability, availability, and maintainability (RAM) analyses (i.e., the average rate of repair completions is assumed time-independent, leading to exponential distributions for repair down times). In general, if other types of probability distributions are used to characterize operating time between failures and repair downtimes, the quantities in Eq. (1) are to be interpreted as the first moments (mean values) of these distributions.

Taking Eq. (1) as a starting point, we may rewrite this in a form more suitable for parametric analysis:

$$A = \frac{1}{1+x} \ , \qquad (1')$$

where x=MTTR/MTBF. For cases of practical interest here, x will generally be a small number, typically less than 0.1.

The overall system (process line or plant) is assumed to be comprised of a number N of processing subsystems linked in a serial configuration from the viewpoint of RAM analysis. That is, we represent the availability of the overall system or plant as a product of availability factors for N individual subsystems, as follows:

$$A_p = \prod_{i=1}^{N} A_i = \prod_{i=1}^{N} \left(\frac{1}{1+x_i}\right) \quad . \tag{2}$$

This formula is also an approximation, resting on the general assumption that failure-repair cycles for the individual subsystems can be treated as statistically independent events. The approximation will be valid provided that the ratios x_i for the individual subsystems are numerically small, as indicated above. A final basic premise underlying the analysis in this paper is that plant performance goals are strongly linked with achieving high intrinsic availability of the process systems.

3. INFLUENCE OF MAINTENANCE SYSTEM FAILURES AND REPAIRS

The MTTR parameters and associated probability distributions in the above model are generally estimated under the assumption that the maintenance equipment is deployed under ideal circumstances (i.e., conditions in which maintenance equipment is not itself subject to failures). This work next examines how failures in the maintenance system might influence overall process plant availability.

In the following analysis, any equipment complex (system) that is (1) used to carry out repair operations, (2) subject to breakdowns, and (3) repaired by functionally separate maintenance equipment will be referred to as an M-system. The backup system is generally considered to repair the primary system; however, in the case where these systems are identical or near-identical, the distinction between primary and backup maintenance system may not be significant.

A practical approach to modeling the relationships between process (S) and maintenance (M) system RAM characteristics is to represent the composite system by a Markov probability model such as shown in Fig. 1. In this type of probability model, both states designating the system status at any

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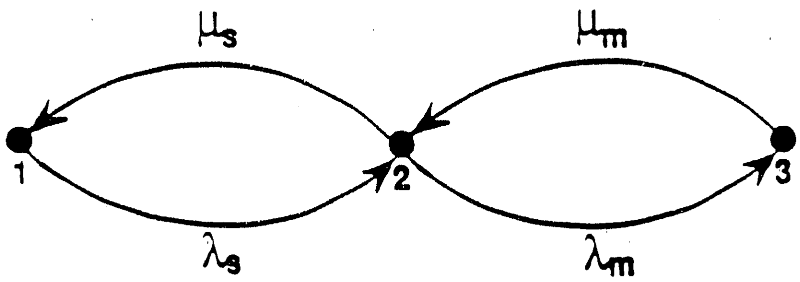
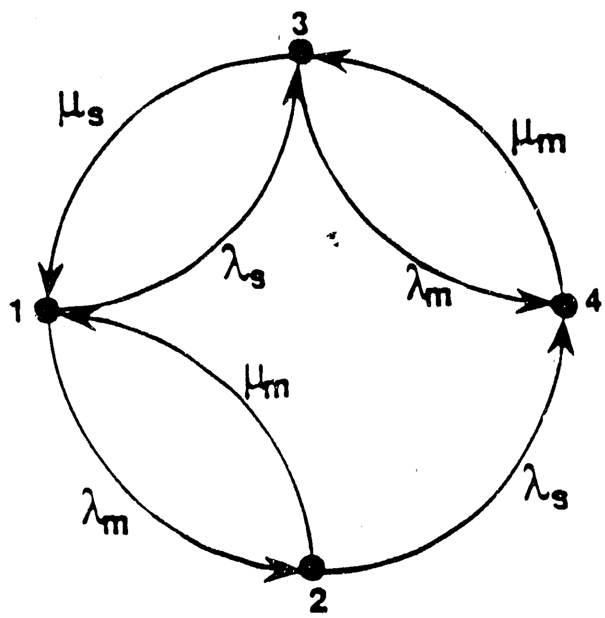


Case (a) where maintenance systems operable on standby.

States:

1. **(S,M) Process (s) and maintenance (m) systems operational.**
2. **($\underline{S}$,M) Process failure, shutdown; maintenance systems operational.**
3. **($\underline{S}$,$\underline{M}$) Both S and M systems failed, under repair.**



Case (b) where maintenance systems subject to interim failures.

States:

1. **(S,M) Process (s) and maintenance (m) systems operational.**
2. **(S,$\underline{M}$) S operational; M-system under repair.**
3. **($\underline{S}$,M) S failed, under repair; M-system operational.**
4. **($\underline{S}$,$\underline{M}$) Both S and M systems failed, under repair.**

Fig. 1. Transition diagrams for Markov models representing failures and repairs in process and maintenance systems.

time and possible transitions between these states are identified. The basic assumption underlying the Markov model is that the probabilities of transitions between states at any given time depend only on the current state of the system and not on the prior history of transitions. Following common notation used in this type of probability modeling, failure probability rates (hazards) are designated by λ and repair probability rates by μ, each expressed in reciprocal time units ($hours^{-1}$). With the assumption of time-independency for these parameters, these may be identified with the reciprocals of the MTBF and MTTR parameters, respectively.

In Fig. 1, two alternative models of this type are depicted, differing conceptually with regard to the possible status of the M-systems at the time a process failure occurs. Case (a) is represented as a three-state model in which it is assumed that the M-system is always available to initiate repairs (i.e., is operable on a standby status) whenever a process line failure requiring shutdown occurs. This is represented by a transition between states 1 and 2. During the repair process, breakdowns may occur in the M-system, leading to a further transition to state 3 in which both process and maintenance systems are inoperable. While holding in state 3, repairs made on the primary M-system using the backup equipment transfers the composite system back to state 2.

For the type of applications of interest here, it cannot be taken for granted that the M-system is always available on standby when a failure occurs in a process subsystem. Other duties (e.g., operational or maintenance tasks elsewhere within the total system or plant) can lead to breakdowns in M-system components, independent of status of the process subsystem. In the second case (b) depicted in Fig. 1, a fourth state is added to account for the possibility of a failure/shutdown occurring in a process subsystem, at a time when the M-system was also under repair, as a consequence of failures occurring during other routine operations. In the diagram, this situation would be represented by a transition between states 2 and 4. Before any repairs on the process equipment can be undertaken, the M-system must be repaired using the backup equipment, and this is represented by the link designated μ_m between states 4 and 3. This presumes that repair of the primary M-system must be given priority [i.e., no unnecessary risks should be taken by first completing process repairs using the backup M-system (if this is feasible), because failure of the latter would greatly complicate prospects for repairs within the hostile environment]. The transitions between state 3 and states 1 or 4 may be interpreted by noting that the top half of the transition diagram for case (b) is equivalent to that for case (a).

In case (a), the process subsystem availability is identified with the probability of finding the system in state 1; in case (b), it is the sum of probabilities for states 1 and 2. The steady-state solutions for these probabilities can be obtained using standard methodology applicable in Markov models for availability analysis (ref. 1).

The resulting mathematical analysis, as expressed for process subsystem availability for the two cases, give:

$$\text{Case(a)} \qquad A_s = \frac{1}{(1 + x/A_m)} \quad , \tag{3}$$

$$\text{Case(b)} \qquad A_s = \frac{1}{\{1 + x[1 + \alpha(1 - A_m)/A_m]\}} \quad , \tag{4}$$

$$A_m = \frac{1}{(1 + \lambda_m/\mu_m)} \quad , \tag{5}$$

$$\alpha = 1 + \frac{\mu_s}{\lambda_s + \lambda_m + \mu_m} \approx 1 + \frac{\mu_s}{\mu_m} \quad . \tag{6}$$

In deriving these equations, we have identified λ/μ with x, the parameter defined in Sect. 2 for calculating process availability.

Note, by comparing Eq. (1′) with Eq. (3) for case (a), that the net effect of maintenance system failures is to replace x by x/A_m. This is also equivalent to multiplying the process equipment repair rate parameter, μ_s, by the maintenance system availability, a result readily interpreted on intuitive grounds. In case (b), the new parameter α emerges when the possibility is considered that the M-system can be in a failed condition when it is required for process maintenance. The last approximation expressed in Eq. (6) holds if the average time between failure is large compared to average repair times (i.e., $\lambda_s + \lambda_m << \mu_m$). The availability formula for case (b) becomes identical with case (a) if α is equated to unity.

Part of the shutdown time associated with a process equipment failure may be utilized for system diagnosis, logistical purposes, etc., not requiring full capabilities of the remote-handling equipment. In principle, therefore, failures in the maintenance equipment would affect process equipment repair rates only if the maintenance equipment were inoperable when actually needed for the process repair work. This can be accounted for approximately in the preceding analysis by splitting the MTTR parameter (which equals $1/\mu_s$) into two components, with fraction ß associated with the actual time the M-systems are on demand and fraction 1-ß associated with other activities (e.g., failure diagnosis). The net effect is to replace Eqs. (3) and (4) by the following formulas:

$$A_s = \frac{1}{[1 + x(1 - \beta + \beta/A_m)]} \quad , \tag{3'}$$

$$A_s = \frac{1}{\{1 + x[1 + \beta\alpha(1 - A_m)/A_m]\}} \quad . \tag{4'}$$

Note that in all cases the net effect is to multiply the process failure/repair rate ratio x by a quantity which varies inversely with the maintenance system availability.

To numerically investigate the relationship between M-system availability and overall plant availability, we first specialized Eq. (2) to the case of a serial configuration of N subsystems having identical failure/repair characteristics (i.e., $x_i = x$ for all i) and treated x and N as parameters:

$$A_p = (A_s)^N = \left(\frac{1}{1+x}\right)^N , \tag{7}$$

Thus, the calculations involved the combined use of Eqs. (3) through (7). As a baseline for evaluations, the remote maintenance equipment was assumed, on the average to be required during one-half of the total shutdown time [i.e., $\beta = 0.5$ in Eqs. (3′) and (4′)]. The process line or plant availability was calculated as a function of M-system availability, choosing values of x to be representative of process system characteristics.

The results of some calculations based on these models are shown in Fig. 2. Two sets of curves are exhibited. The solid lines correspond to case (a) in Fig. 1, where the maintenance systems are considered to be on a standby status when needed. The dashed curves illustrate case (b) of Fig. 1, wherein the M-system may be inoperable on demand for process equipment repair. For these calculations, μ_s was assumed approximately equal to μ_m so that $\alpha \approx 2$ in accordance with Eq. (6).

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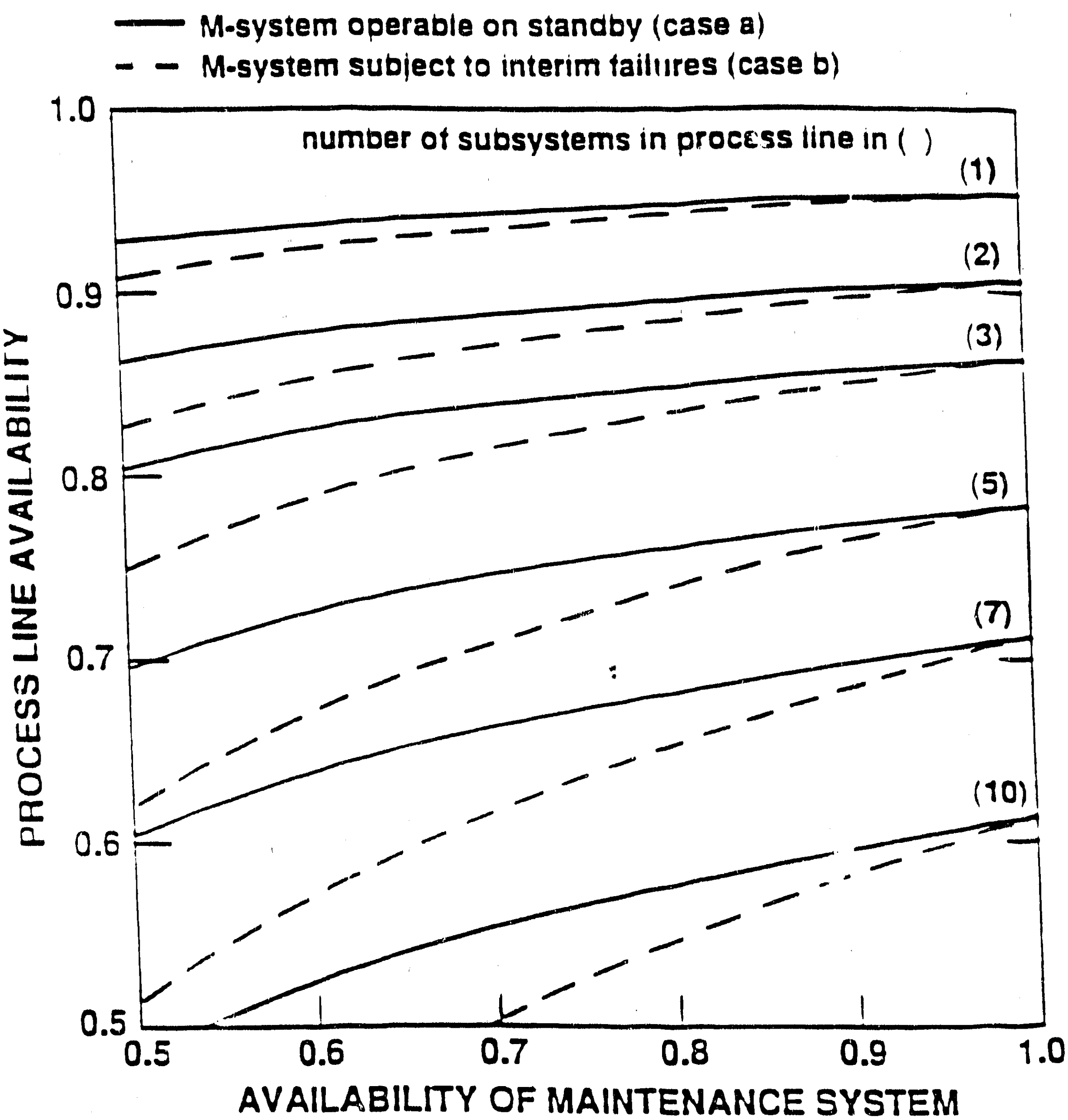

Fig. 2. Dependency of process line availability on maintenance system availability, subsystem ratio MTTR/MTBF = 0.05.

These calculations indicate that a low intrinsic availability of the M-system could significantly reduce process line availability. This effect increases with the number of serially linked stages of the process line. For example, if x=.05 for each of ten process subsystems, the calculated plant availability with ideal (non-failing) maintenance equipment is 61%. If the M-system availability were 70%, plant availability would be reduced to 55 or 50%, depending on the applicability of model (a) or (b), respectively.

4. EFFECTS OF PARTIAL FAILURES IN SERVOMANIPULATORS

All of the analyses given above are based on the assumption that a failure in either process or maintenance equipment will require repairs to be undertaken before further operation. In certain cases, however, operations can continue even if the maintenance equipment has degraded capabilities. For the advanced EMSs used in remote handling and maintenance, performance tends to be a continuum, ranging from fully functional to completely inoperative. Although this situation is not readily amenable to analysis, a suitable approximation which provides insight into the effects of operating with degraded equipment capabilities is to introduce an intermediate state for the M-system, between that of fully functional (operating) and totally inoperative (failed).

The analysis described in Sect. 3 was extended to model this degraded operation situation. The state of the composite system (process equipment plus maintenance equipment) was again represented by a Markov probability model. The 3-state and 4-state aggregate representations shown in Fig. 1 were replaced by a 6-state representation, as shown in Fig. 3. Table 1 is a list of definitions of the symbols used in this diagram.

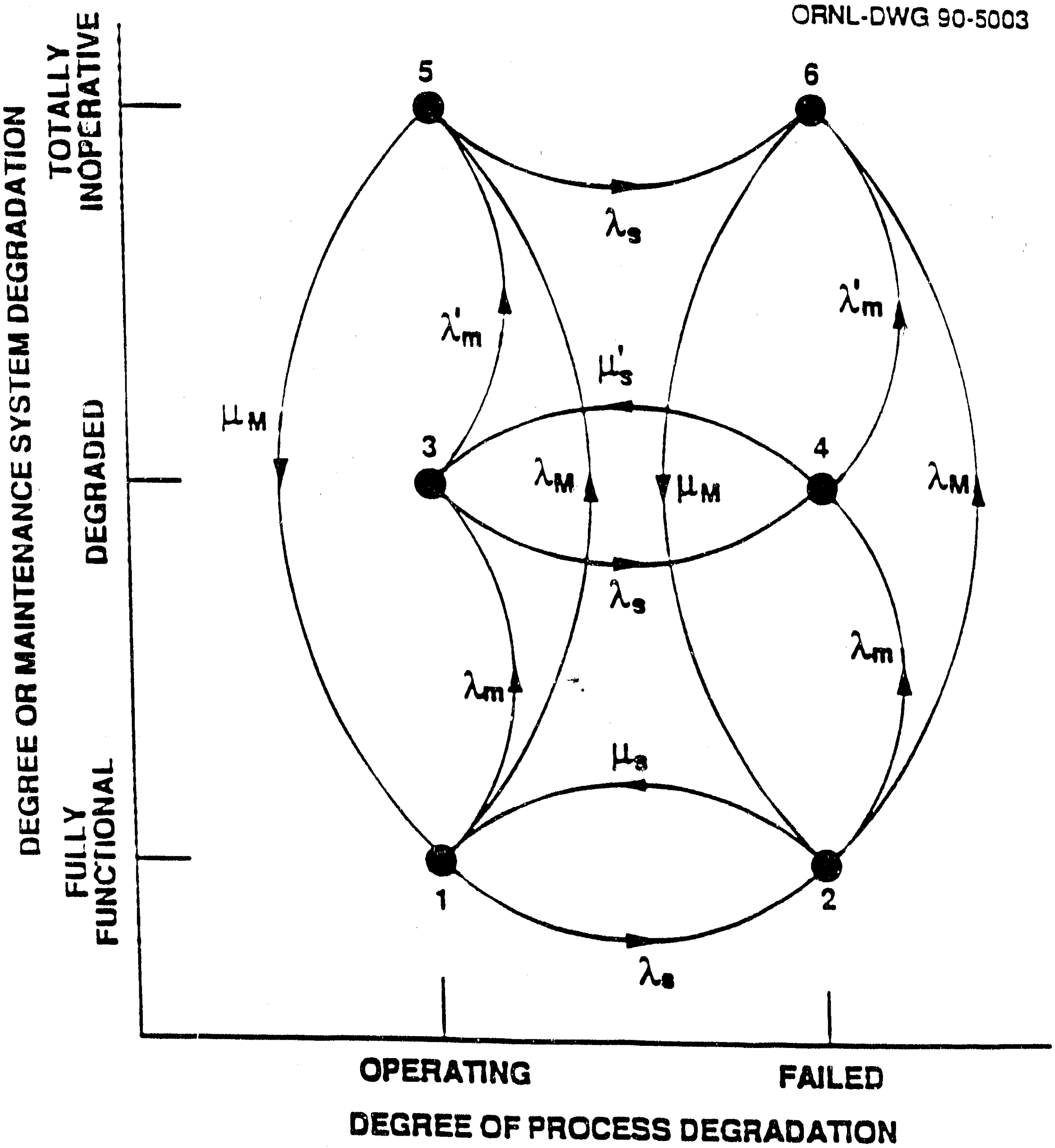

Fig. 3. Transition diagram for the 6-state Markov model used in this study.

Table 1. Summary of parameter definitions for Fig. 3.

Failure-rate parameters:	
λ_s	Process equipment transitions to an inoperable condition.
λ_m	Failure transitions which result in degraded EMS performance capabilities.
λ''_m	EMS failure transitions from a degraded to a totally-inoperative condition.
λ_M	Failure transitions for components of maintenance system other than the EMSs, leading directly to totally-inoperative condition.
λ'_m	Failure transitions of total maintenance system from degraded to a totally inoperative state (sum of λ_m'' plus λ_M).
Repair-rate parameters:	
μ_s	Process repair rate assuming no degradation of maintenance equipment.
μ'_s	Process repair rate assuming degraded EMS performance capabilities.
μ_M	Repair rate for maintenance equipment from a totally inoperable condition.

To interpret this two-dimensional diagram, consider that position along the horizontal direction represents the degree of degradation in process equipment performance. Here, two possible states are assumed—operating or failed. Position along the vertical direction represents the degree of degradation in maintenance equipment performance. Here, three states are considered: fully functional, operating with degraded capabilities, and totally inoperative. Possible transitions between these states are indicated by the arrows in the diagram.

The mathematical procedures required for calculating the steady-state probabilities associated with this diagram are similar in principle to those used for the 3- and 4-state descriptions. While the 4-state description was still amenable to algebraic solution, models using larger numbers of possible states, such as described in Fig. 3, require computer procedures. The Lotus 1-2-3 software was found to be readily adaptable for this purpose.

The mathematical analysis also showed that the steady-state availabilities are governed by certain combinations of ratios of failure and repair-rate parameters, rather than by their absolute magnitudes. (Note that the same is true of the simpler availability models discussed in Sect. 3; here, however, more ratio quantities are involved due to the higher dimensionality of the model.) If we arbitrarily select μ_s, the reciprocal of the mean down time required for repair of a typical process subsystem using fully-functional EMSs, as a basis for normalizing these ratios, the following combinations of parameters determine the probabilities:

$$\frac{\lambda_s}{\mu_s}=x \quad ; \quad \frac{\lambda_m}{\mu_s}=y \quad ; \quad \frac{\lambda_M}{\mu_s}=z \quad ; \tag{8}$$

$$\frac{\mu_M}{\mu_s}=a \quad ; \quad \frac{\mu_s'}{\mu_s}=b \quad ; \quad \frac{\lambda_m''}{\lambda_m}=c \quad .$$

$$\frac{\lambda_m'}{\mu_s} = \frac{(\lambda_m'' + \lambda_M)}{\mu_s} = c \cdot y + z \quad . \tag{9}$$

Applications of this model reduced to investigating the dependency of the state probabilities on the parameter set x, y, z, a, b, and c. The first three prescribe ratios of specific failure rates to repair-rate parameters, while the last three involve ratios of the repair times and ratios of failure rates. Approximate ranges of interest were prescribed for these parameters. Referring to the above parameter definitions, the parameter a would be determined by characteristics of the backup M-system (which influences the MTTR for the primary maintenance equipment). It would likely have its largest magnitude, of the order of unity, if the backup were an identical system with fully-functional EMSs. It could have its smallest magnitude if no backup systems were present in the process cell, making it necessary to disconnect and transport the failed equipment to another cell for repair. Thus, such considerations caused the range a = 1.0 to 0.25 to be investigated in these calculations. The parameter b measures the degree of degradation in performance capabilities (average down time requirements are inversely proportional to b). Its range of variation could be somewhat less than the variation in average time required to perform typical tasks using degraded EMSs, since a portion of the down time is normally utilized for diagnosis and logistical purposes, not requiring full EMS capabilities. For these calculations, a range of b=1 to 0.25 was considered. The parameter c depends on specific design characteristics of the EMSs. Calculations showed that the process subsystem availabilities were relatively insensitive to this parameter, and a value of c=1 was assumed for the calculations described here. Finally, the values considered for parameters x, y, and z were based on typical results derived from past analyses for specific equipment complexes within a reprocessing facility.

The model was used to investigate some specific questions:

1. Under what conditions is there a net gain in process availability from operating the EMSs with degraded performance capabilities, instead of first effecting their repair using the backup equipment?
2. How do the estimated availabilities for process and maintenance systems depend on the frequency of failures and EMS degradation (parameter y); the degree of degradation (parameter b); and the efficiency of the backup maintenance system (parameter a)?

For all the calculations, a representative value of $x = 0.05$ for the process equipment failure/repair ratio was assumed. A value of $z=0.1$ was assumed to characterize the rate of failures in components of the primary M-system, leading to total loss of function. The range $y = .05$ to $.20$ was selected to span possible failure rates for the electro-mechanically complex EMSs.

As a baseline for comparisons (case 1), the model was first used for the situation with no degraded operations of the EMSs. Formally, this requires setting $\lambda_m = 0$ in Fig. 3 and letting λ_M represent the sum of probabilities for all types of maintenance equipment failures, including the EMSs. The reduced diagram, with states 3 and 4 inaccessible, is equivalent to the 4-state model (b) of Fig. 1.

In case (2), it was assumed that the EMSs were repaired only after becoming fully inoperative (i.e., after additional failures had resulted in transitions from states 3 or 4 to states 5 or 6 in Fig. 3). Finally, case (3) was constructed to represent an intermediate case wherein degraded operation of the EMSs is allowed under conditions of process failure (state 4), but once process repairs are completed (transition to state 3) priority is given to repair of the EMSs. Formally, this requires deleting the failure transition linking states 3 and 5 in Fig. 3 and substituting a repair transition linking states 3 and 1 (not shown).

Some results of these calculations are summarized in Table 2. Note that the process availability in these tables is defined as the sum of the steady-state probabilities for states 1, 3, and 5 in Fig. 3. The M-system availability is defined as the sum of probabilities for states 1 and 2 in case (1), states 1, 2, 3, and 4 in case (2), and states 1, 2, and 3 in case (3). Note also in interpreting these results that numerically small changes in the calculated availability for the process subsystem can become significant when considering a serial configuration of subsystems, comprising a process line or plant. As an example, in accordance with Eq. (7), for a line consisting of 10 similar subsystems, a decrease of .01 in subsystem avaiability, A_s could reduce overall plant availability by about 10 percent.

The most significant inference drawn from these calculations is that there could be a slight advantage in permitting degraded operations of the EMSs, postponing repairs at least until process operations are restored, provided the degradation is not too severe, [e.g., mean down times for repairs are not increased by more than about a factor of two (b>0.5)]. In Table 2, the situation where backup M-system capabilities are comparable to the primary equipment (a=1), this follows by comparing process availabilities for cases (1) and (3). At b=0.5, there would be relative indifference between continuing with degraded EMSs or first repairing them. The advantage in permitting degraded operations is less distinct for case (2), that of postponing EMS repairs until the M-system becomes completly inoperable. This mode might need to be considered, however, if other system demand priorities were being placed on the M-system.

If the capabilities or efficiency of the backup maintenance equipment were significantly less than the primary equipment (Table 2 with a = .5), the advantage of permitting degraded EMS operations could be even more pronounced. A calculated advantage appears for both cases (2) and (3), for b larger than 0.5, and is still present in the latter case for somewhat greater degrees of degradation.

Table 2: Illustration of calculations with 6-state Markov Model*
(x = .05; y = .10; and z = .10)

			Availability					
a*	b*		Process subsystem (S)			Maintenance system (M)		
		Case no:	(1)	(2)	(3)	(1)	(2)	(3)
1.0	1.0		.936	.941	.944	.833	.882	.834
	0.5			.928	.937		.882	.835
	0.25			.911	.929		.882	.836
0.5	1.0		.912	.924	.930	.714	.789	.717
	0.5			.910	.921		.789	.719
	0.25			.892	.908		.789	.721

*Note: "a" is relative measure of backup maintenance system efficiency.
"b" is relative measure of degradation in EMS capabilities.

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GOALS

- Plant performance goals are often linked with achieving high intrinsic availability of process equipment.

- It is typically assumed that the maintenance system is available to conduct repairs when called upon by plant equipment failures.

- However, maintenance systems are themselves often complex and subject to breakdowns.

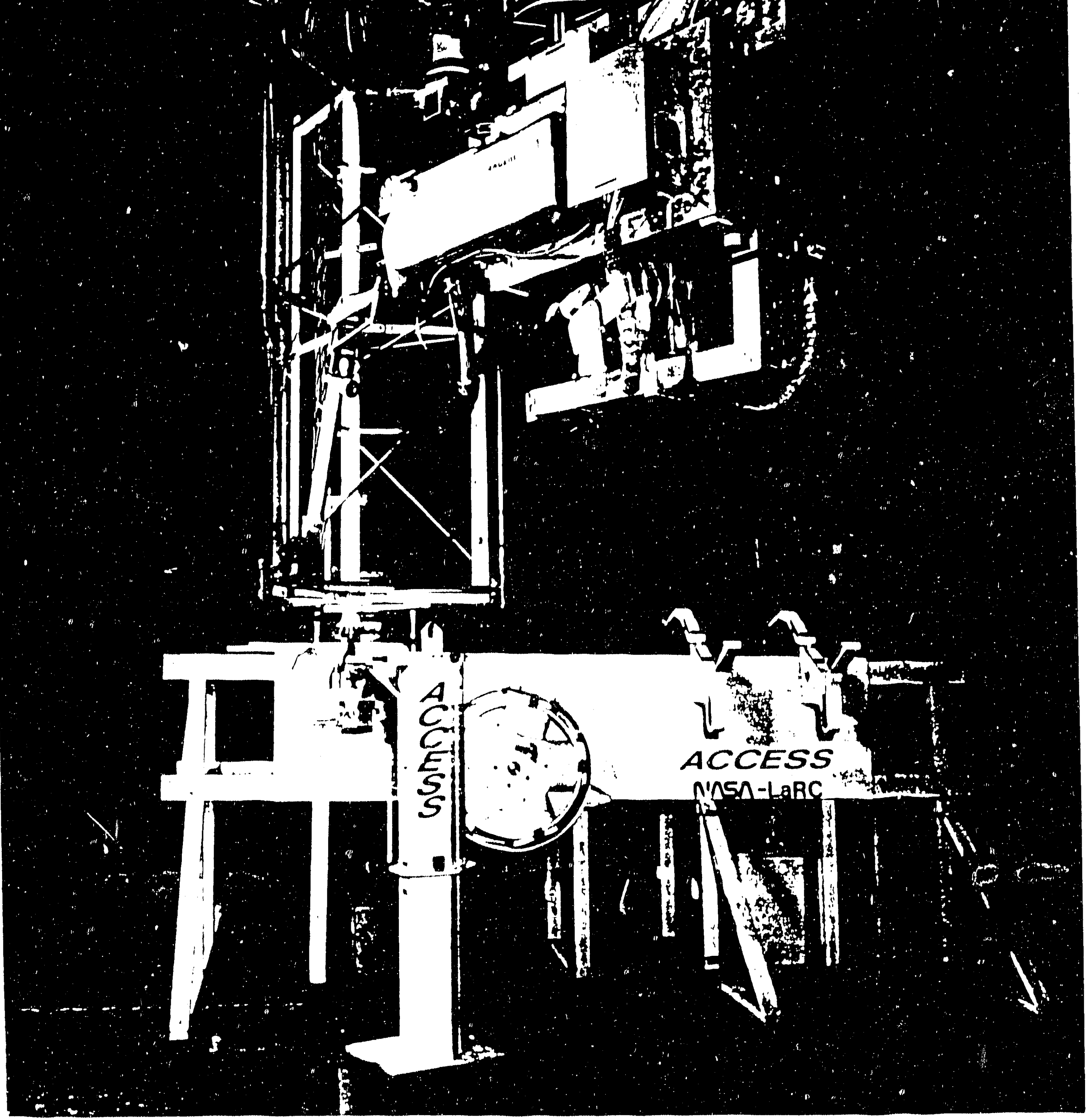
ILLUSTRATION OF APPLICATIONS THAT MOTIVATED THIS ANALYSIS

Fig. 1: Experiment demonstrating installation and repair of struts on space station.

Fig. 2: Electro-mechanical servomanipulator with prototype nuclear fuel reprocessing plant equipment rack.

Fig. 3: Servomanipulator replacing pump.

Fig. 4: Control room for remote maintenance system.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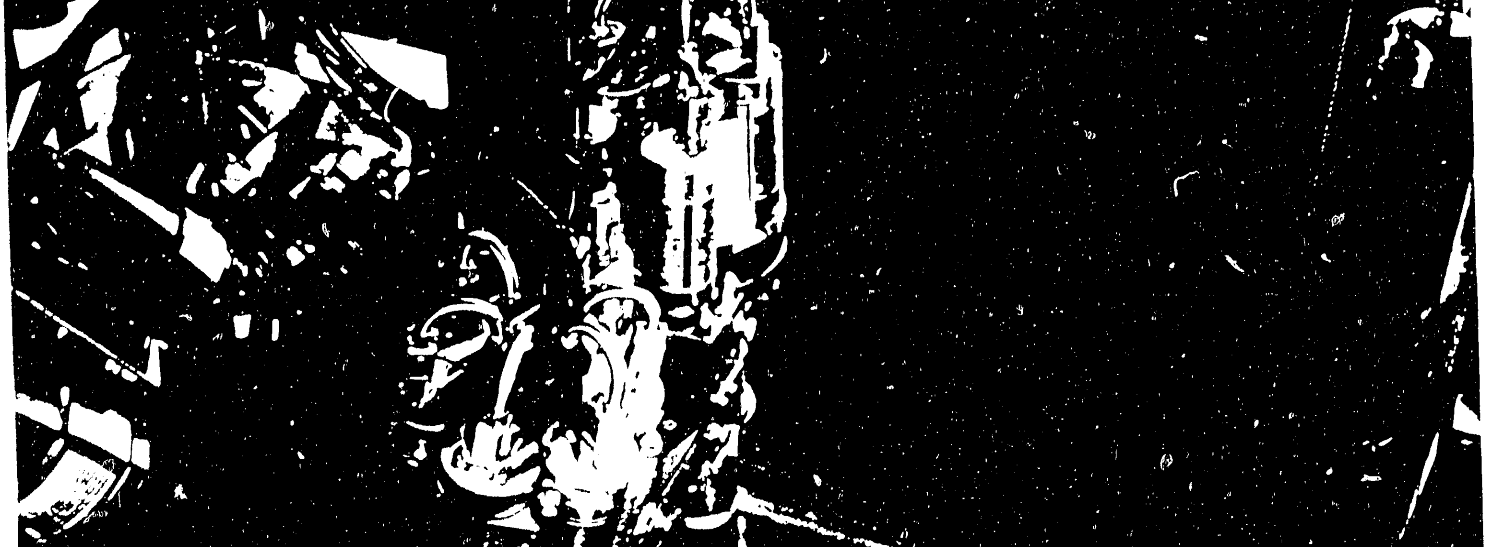

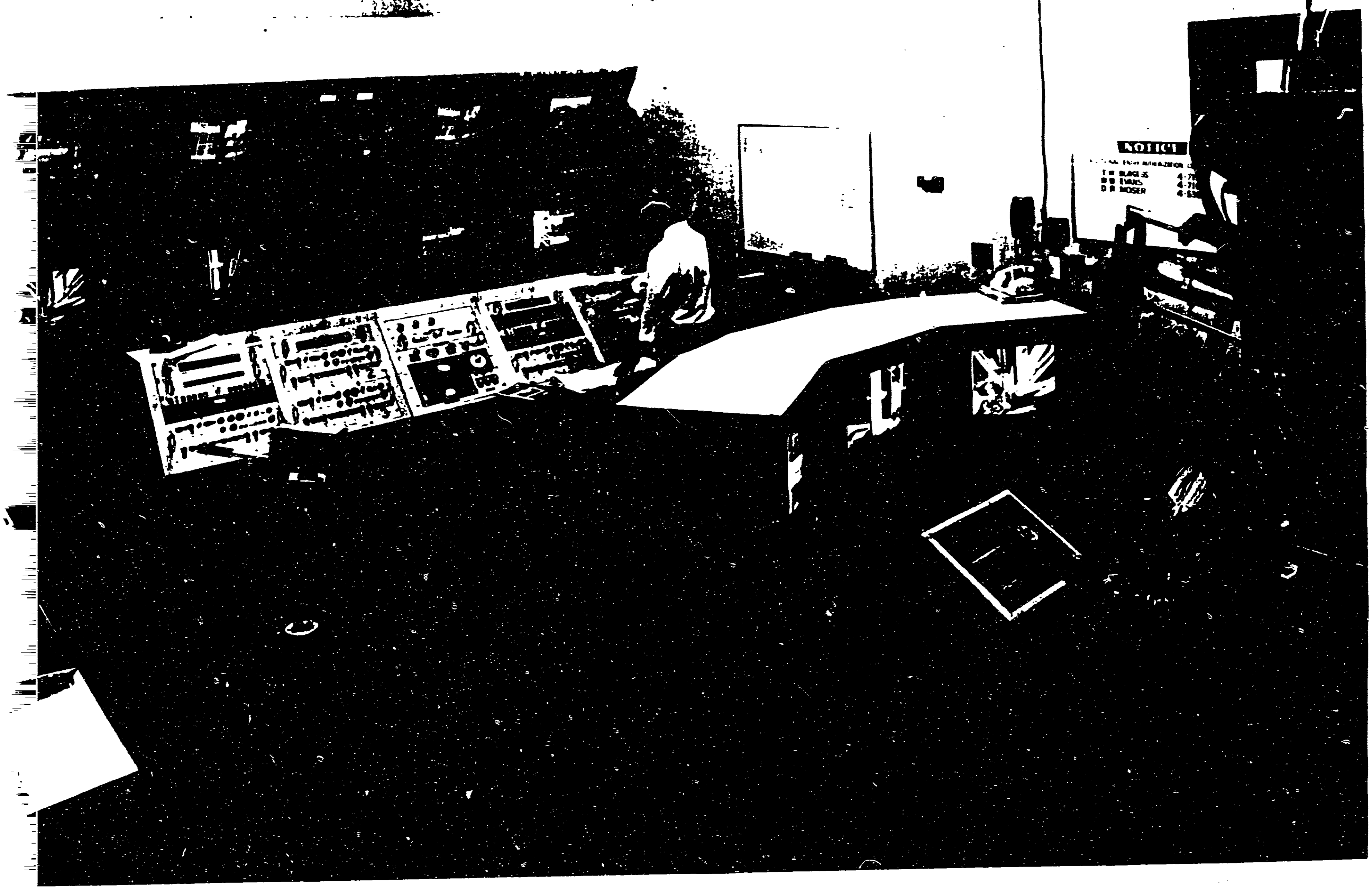
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- There is a need to develop guidelines that relate performance characteristics of maintenance systems to plant equipment systems.

- A practical approach to modeling reliability, availability, and maintainability relationships between plant and maintenance equipment is to represent the composite system by a Markov probability model.

USE OF MARKOV MODELS

Several Markov models were used to investigate the following questions.

- How do the failure and repair characteristics of maintenance equipment influence the expected availability of a series configuration (line) of process subsystems?

- What is the effect of allowing some degradation in maintenance equipment capabilities?

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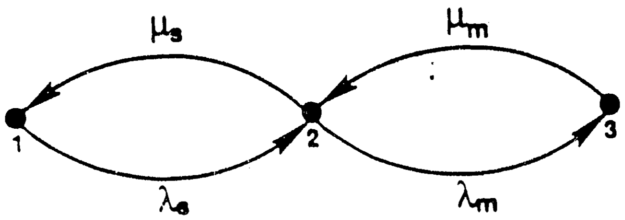
TRANSITION DIAGRAMS FOR MARKOV MODELS REPRESENTING FAILURES AND REPAIRS IN PROCESS AND MAINTENANCE SYSTEMS



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  3. ($\bar{S}$,$\bar{M}$) — Both S and M systems failed, under repair

ALGEBRAIC FORMULATIONS OF STEADY-STATE AVAILABILITIES

Case (a): Maintenance system operable on standby when process subsystem failure occurs (3-state model).

$$A_S = \frac{1}{1 + X/A_m}$$

where, by definition:

$$X = \lambda_s/\mu_s$$

$$A_m = \frac{1}{1 + \lambda_m/\mu_m}$$

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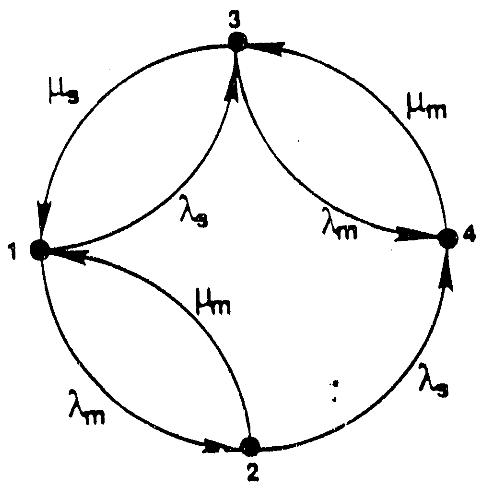
TRANSITION DIAGRAMS FOR MARKOV MODELS REPRESENTING FAILURES AND REPAIRS IN PROCESS AND MAINTENANCE SYSTEMS



- Case (b): Maintenance systems subject to interim failures.

  States:

  1. (S,M) — Process (s) and maintenance (m) systems operational
  2. (S,$\bar{M}$) — S operational; M-system under repair
  3. ($\bar{S}$,M) — S failed, under repair; M-system operational
  4. ($\bar{S}$,$\bar{M}$) — Both S- and M-systems failed, under repair

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ALGEBRAIC FORMULATIONS OF STEADY-STATE AVAILABILITIES

- Case (b): Maintenance equipment subject to interim breakdowns, between failures in process subsystem (4-state model):

$$A_s = \frac{1}{1 + X[A_m + \alpha(1 - A_m)]/A_m}$$

where, by definition:

$$\propto = 1 + \frac{\mu_s}{\lambda_s + \lambda_m + \mu_m} \approx 1 + \frac{\mu_s}{\mu_m}$$

- Process line (plant) represented parametrically as a series configuration of N equipment complexes (subsystems), each having the same failure/repair ratio, X.

$$A_p = A_1 * A_2 * \cdots * A_N = (A_S)^N.$$

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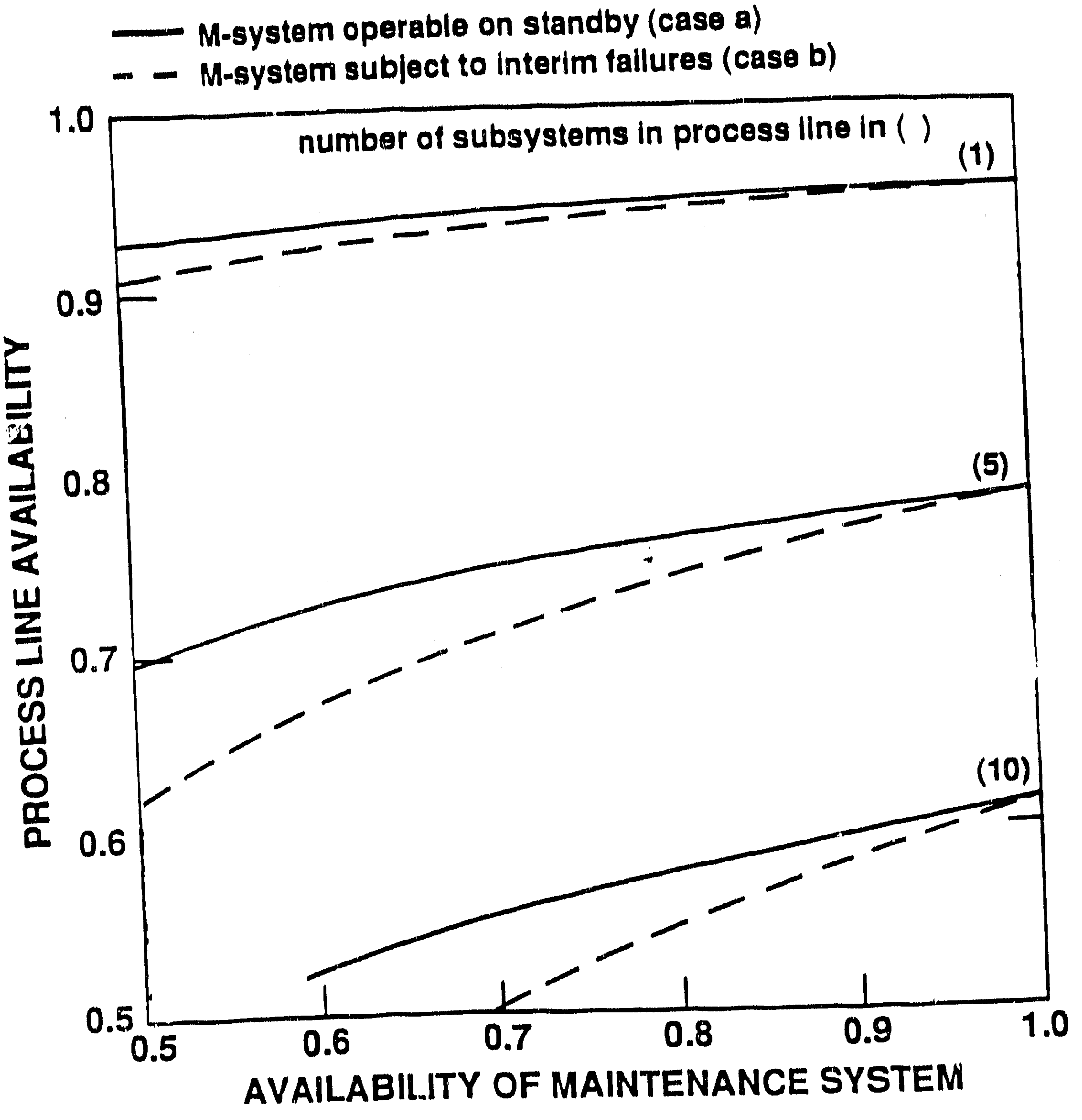
DEPENDENCY OF PROCESS LINE AVAILABILITY ON MAINTENANCE SYSTEM AVAILABILITY (subsystem MTTR/MTBF = 0.05)



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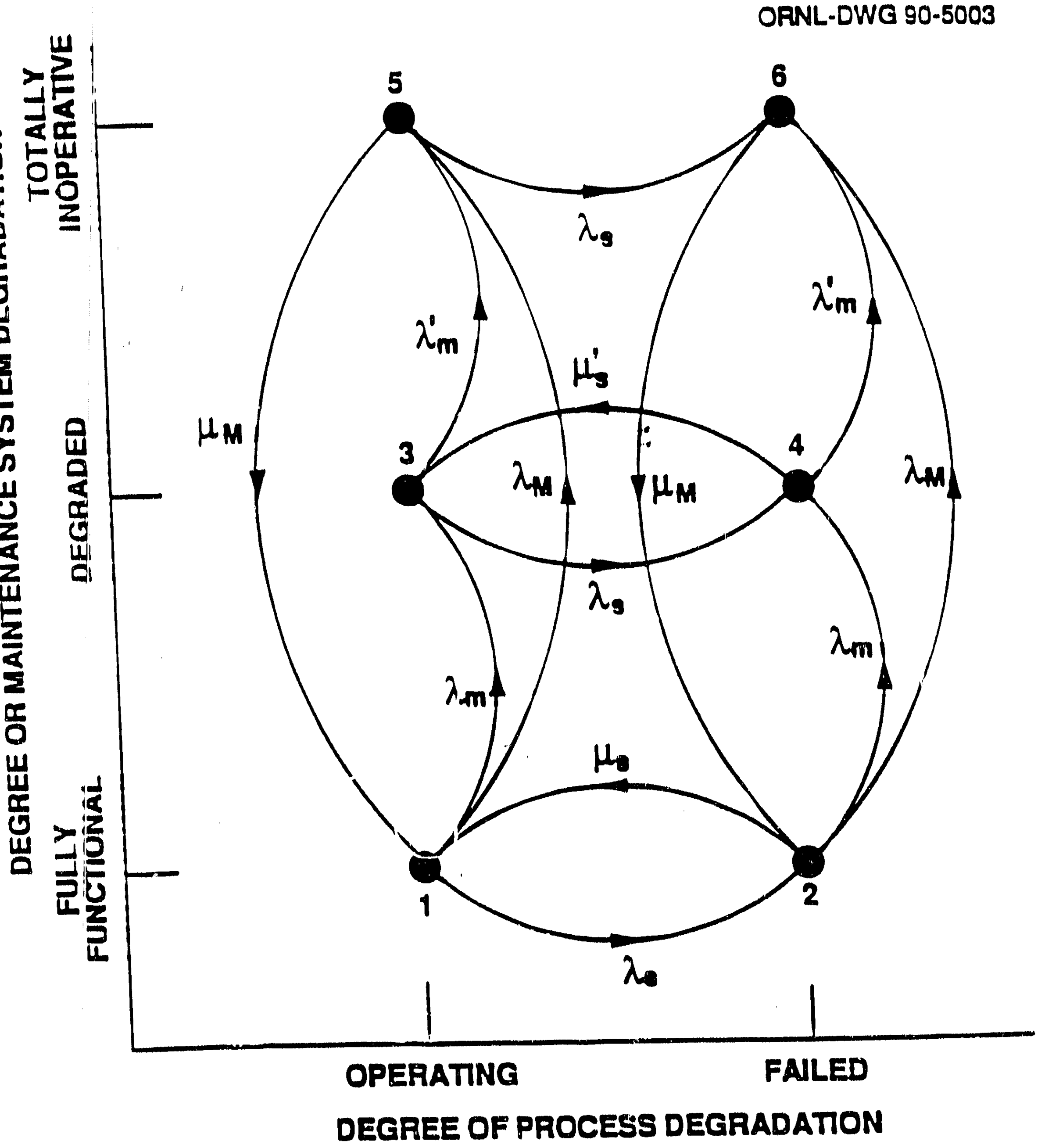
- Maintenance activities can often continue even if some failures cause degradation of equipment capabilities.

- For advanced electro-mechanical servomanipulators (EMS), performance tends to be a continuum, ranging from fully-functional to totally-inoperative.

TRANSITION DIAGRAM FOR DEGRADED OPERATION USING A 6-STATE MARKOV MODEL



- Mathematical analysis shows system availabilities are governed by certain ratios of failure and repair-rate parameters in 6-state Markov model. Of these, most significant were:

$x = \frac{\lambda_s}{\mu_s}$, measures RAM characteristics for process equipment, assuming full (ideal) capabilities of maintenance systems.

$y = \frac{\lambda_m}{\mu_s}$, measures failure rate of degradation in EMS capabilities, relative to process repair rates under ideal conditions.

$z = \frac{\lambda_M}{\mu_s}$, measures failure rates in maintenance equipment leading to total inoperability, relative to ideal process repair rates.

- Mathematical analysis shows system availabilities are governed by certain ratios of failure and repair-rate parameters in 6-state Markove model. Of these, most significant were: (continued)

$a = \frac{\mu_M}{\mu_s}$, measures repair efficiency of backup maintenance equipment, relative to ideal process repair rates.

$b = \frac{\mu_s'}{\mu_s}$, measures degree or degradation in EMS capabilities, relative to ideal process repair rates.

- 6-state model was used to investigate some specific questions:

  - Under what conditions is there a net gain in process availability from permitting operation of the EMSs with degraded performance capabilities?

  - How do the estimated availabilities depend on the repair efficiency of the backup system (parameter a) and the degree of degradation in primary maintenance system (parameter b).

- Three cases were examined:

  (1) Base case; no degraded operation of EMSs permitted.
  (2) EMSs repaired only after becoming completely inoperative.
  (3) Degraded operations permitted until process repairs are complete; priority then given to EMS repairs.

- Table 1 illustrates results of some calculations made in examining these questions.

Table 1: Illustration of calculations with 6-state Markov Model*
(x = .05; Y = .10; and Z = .10)

			Availability					
a*	b*		Process subsystem (S)			Maintenance system (M)		
		Case no:	(1)	(2)	(3)	(1)	(2)	(3)
1.0	1.0		.936	.941	.944	.833	.882	.834
	0.5			.928	.937		.882	.835
	0.25			.911	.929		.882	.836
0.5	1.0		.912	.924	.930	.714	.789	.717
	0.5			.910	.921		.789	.719
	0.25			.892	.908		.789	.721

*Note: "a" is relative measure of backup maintenance system efficiency.
"b" is relative measure of degradation in EMS capabilities.

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CONCLUSIONS DRAWN FROM THE ANALYSIS

- Process plant availability can be signficantly affected by failures in maintenance equipment.
- A single approximate rule for estimating magnitude of effect is to multiply process equipment repair rates under ideal conditions (μ_s) by the expected availability of primary maintenance system (Am)
- Process availability may be improved slightly by permitting some degradation of maintenance equipment (EMS), before giving priority to repair.
- Approximate rule indicated by these calculations is to permit process equipment repairs using degraded EMSs, provided repair times are not increased by more than about a factor of two.

END

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