

## A RELIABILITY MODEL TO BALANCE THE BENEFICIAL AND ADVERSE IMPACTS OF MAINTENANCE\*

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### ABSTRACT

This paper describes a component-level maintenance model to evaluate the impact of maintenance on a component's performance. The model uses a Markov approach to include both the beneficial and adverse effects of maintenance which considers the degraded state of a component, in addition to its operational state and failed state. The beneficial effect of maintenance relates to its effect in improving the reliability of the component, i.e., maintenance corrects degradations before failures occur. The adverse effects of maintenance includes maintenance downtimes and maintenance-related errors, which traditionally are included in component-level models of a probabilistic risk assessment. We present example applications of the model and discuss uses of the results obtained from such an analysis. The model will provide a quantitative basis for making decisions on maintenance to achieve the level of component performance desired.

### I. INTRODUCTION

Maintenance plays a significant role in ensuring the availability and reliability of components and, thus, is an important contributor to reducing plant risk. During power operation, corrective maintenance is undertaken to repair any failure due to degradation of the equipment, while scheduled preventive maintenance ensures its reliability.

Currently, maintenance is modeled in PRAs relatively simply and does not cover its many effects. The PRAs include only the unavailability of equipment due to maintenance downtimes; this is the adverse effect of maintenance.

Further, in many cases, unavailability only includes the downtimes for corrective maintenances, and not scheduled preventive maintenance. The beneficial aspect of maintenance, in terms of its enhancement of the equipment's reliability, is not modeled directly.

Improving maintenance models to include both the beneficial and adverse effects of maintenance is important in addressing many safety issues during operation:

1. for applying and implementing the NRC maintenance rule
2. for balancing the beneficial aspects of maintenance with downtime unavailability
3. for optimizing the maintenance to be performed during power operation versus plant shutdown
4. for understanding and mitigating the effects of aging on plant safety.

In addition, by improving the model, the cost-benefit aspect of maintenance can be addressed more comprehensively.

In this paper, we discuss a reliability modeling approach which quantifies both the adverse and beneficial effects. Such a model can be used to address the operational safety issues listed above.

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## II. MODELING BENEFICIAL AND ADVERSE EFFECTS OF MAINTENANCE

Standard reliability approaches and standard probabilistic risk assessments (PRAs) assume two states for each component, a success state and a failed state. A principle benefit of maintenance is to correct degradations before failures occur. Thus, this benefit is not quantified in PRAs which do not include the degraded states of components. However, including failed state allows the adverse effects of maintenance to be quantified: maintenance downtime, and possible maintenance-related errors.

A Markov approach was developed for quantifying the effects of maintenance by defining a degraded state for the component, in addition to an operational state and a failed state.<sup>1,2</sup> The Markov maintenance model is a natural extension of the standard models and can be simplified for PRA models when the degraded state is not differentiated from the operation state.

A component is degraded when its performance falls below some threshold value defining the normal designed performance; in this state, the component is still functional but has a larger likelihood of failure. A standard PRA lumps the degraded state with the operational state; in our modeling approach, they are separated.

We define four states for the component which we denote by o, d, m, and f (also, see Table 1):

- o: the component's operational state reflecting normal designed performance
- d: the component's degraded state reflecting degraded, but functional performance
- m: the component's state of maintenance in which it is down for maintenance

and

- f: the component's failed state in which it is functionally failed or being repaired.

If a piecepart of a component instead of the component itself is the focus of maintenance, then the above definitions apply accordingly.

Table 2 identifies the possible one-step transitions, or state changes for this model. Transitions from one state to the same state are not defined because these are not changes.

When the initial state is an operational state, a possible transition can occur to either a maintenance, a degraded, or a failed state. The possible transition from an operational state directly to a failed state represents a catastrophic failure occurring without an intermediate degraded state first existing. When the component is in a degraded state, then it can proceed to a maintenance state, or to a failed state if it cannot be repaired in time to correct the degradation. A transition from a degraded state to an operational state cannot occur without the component first going through a maintenance state; hence, there is no such transition.

After maintenance, a component can be restored to an operational state or can be left in a degraded or a failed state. Thus, the possibility of ineffective maintenance is considered. Similarly, when the component has failed, then, after repair, it can be in an operational state or can be left in a degraded state. Transitions from a failed state to another failed state are not considered because this is not a change.

It is important to realize that the transition matrix shown in Table 2 defines the possible one-step changes. The component may progress from one state to any other state, but this requires a series of transitions or steps. For example, the component may progress from a degraded state to an operational state by first moving to a maintenance state, and then moving to an operational state. Alternatively, the component may progress from a degraded state to a failed state, then from the failed state to the operational state. When there are several possible one-step transitions from a given state, then transitions may occur to any one of these alternative states. Thus, Table 2 defines the basic process by which a component can be represented during its operation and is modeled here.

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Table 1 Component States for the Maintenance Model

COMPONENT STATE	SYMBOL	DESCRIPTION
Operational State	o	The normal designed performance of the component. Performance above the degradation threshold.
Degraded State	d	Minimal functional performance of the component. Performance above the failure threshold, but below the degradation threshold.
Maintenance State	m	The component is being maintained. The component is unavailable because it is down for maintenance.
Failed State	f	The component is functionally failed and thus unavailable.

For the four-state model, we obtain the associated state probabilities, defining the probability of the component being in each of the states.

$p_o$  = the probability that the component is in the operational state (o) at a given time,

$p_d$  = the probability that the component is in the degraded state (d) at a given time,

$p_m$  = the probability that the component is in the maintenance state (m) at a given time, and

$p_f$  = the probability that the component is in the failed state (f) at a given time.

Using the transition rates from one state to another and the Markov modeling approaches, we obtain steady-state solutions for  $p_o$ ,  $p_d$ ,  $p_m$ , and  $p_f$ , given the steady-state reliability performance of the component. The component's unavailability is obtained from these state probabilities, which can be analyzed as a function of the maintenance interval to obtain a maintenance frequency

that balances its beneficial and adverse effects. References 1 and 2 give details of the model.

### III. APPLICATION OF THE MODEL

We discuss two ways to apply the model. These two applications differ on the type of input data that need to be collected. In both cases, we attempt to define the optimal maintenance frequency that balances the beneficial and adverse effects of maintenance.

In the first application, we consider a standby component which is tested periodically, and assume that any downtime required for testing is negligible. The portion of the input data, that can be obtained from PRA data, relate to the following parameters:

component failure rate ( $\lambda$ ) =  $1 \times 10^{-6}/hr.$   
 test interval ( $T$ ) = 730 hrs. (1 months)  
 repair time ( $d$ ) = 72 hrs.

The additional parameters, that are used in the application of the maintenance model, are as follows:

catastrophic failure fraction ( $f_o$ ) = 0.1  
degradation ratio = 10  
maintenance downtime = 72 hrs.  
maintenance interval = variable

The catastrophic failure fraction is the fraction of failures that are catastrophic, i.e., are not preceded by a

degradation. The degradation ratio is the ratio of occurrences of degradations to failures. The maintenance downtime is the downtime associated with correcting degradations. Collection of these parameters requires additional resources and review of component failure/maintenance databases since these parameters are not collected during the development of PRA input data.

Table 2 Possible One-Step Transitions Between States

		Transition State			
		<i>o</i>	<i>d</i>	<i>m</i>	<i>f</i>
Initial State	<i>o</i>	No	Transition to a degraded state	Maintenance performed on an operational component	Failure without passing through a degraded state
	<i>d</i>	No	No	Maintenance performed on a degraded component	Failure from a degraded state
<i>m</i>	The component restored to an operational state after maintenance	The component left in a degraded state after maintenance	No	The component left in a failed state after maintenance	
<i>f</i>	The component restored to an operational state after repair	The component left in a degraded state after repair	No	No	

## DISCLAIMER

- o* = Operational State
- d* = Degraded State
- m* = Maintenance State
- f* = Failed State

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Figure 1 presents the component unavailability as a function of the maintenance interval which is an important result of this model to define a maintenance interval that balances the beneficial and adverse impacts of maintenance. We plot both component functional unavailability (called component unavailability in PRA terminology),  $q_f + q_m$  ( $= 1 - p_o - p_d$ ), and the component performance unavailability,  $q_o$  ( $= 1 - p_o$ ). The component functional unavailability defines the probability that the component is functionally unavailable because it is either down for maintenance or is failed, which includes the repair downtime to correct the failure. The component performance unavailability defines the probability that the component is in operational state, and not in degraded, maintenance, or failed state. The optimal maintenance interval for component functional unavailability is larger than that for component performance unavailability because more maintenance is needed if the component is to be maintained in near perfect condition, i.e., in the operation state, which is being attempted when component performance unavailability is optimized.

Focussing on the plot for component functional unavailability, we note that for this component the optimal interval is approximately 10 months, and is approximately within 8 to 10 months when the effect on unavailability is minimal. However, beyond this range the effect of maintenance on component unavailability can be significant. An interval shorter than the optimal region is dominated by maintenance downtime, while a value longer than the optimal implies increased unavailability due to failure that may result from inadequate maintenance.

In the second application, the input data includes a reference maintenance interval that is currently in place for the component. By including the maintenance interval, the data for degradation occurrences are not needed, i.e., the resources required to obtain input data is significantly reduced. Again, we consider a standby component and effective maintenance and repairs with the following input parameters:

component failure unavailability =  $1 \times 10^{-3}$   
 test interval = 730 hrs. (1 month)  
 maintenance downtime = 72 hrs.  
 reference maintenance interval = 3 months  
 repair downtime = 72 hrs.

Figure 2 plots component functional unavailability against the maintenance interval. Similar to the previous figure, it shows an optimal interval, which for this component's characteristics, is approximately 20 months. Thus, the current maintenance interval can be increased significantly, which also will improve the availability of the

component. This application shows that with relatively minimal data which can be easily gathered, the model can provide useful information on the best maintenance interval.

#### IV. USE AND INTERPRETATION OF THE RESULTS

The maintenance model provide useful information in defining maintenance for safety system components in nuclear power plants. The results can be used to define the frequency of maintenance, the need to perform on-line maintenance, i.e., maintenance while the plant is operating at power, and the need for reducing maintenance down-times.

The optimal range for the frequency of maintenance can be used to define maintenances for the component; this will assure its reliable performance, and will reduce the need for corrective maintenances. The maintenance frequency obtained with the model may imply less maintenance is required, so reducing the cost and the associated downtime, or alternatively, that more maintenance is needed, which will reduce failures of the component that may be the result of inadequate maintenance. Engineering and practical considerations also should be used to decide on a maintenance frequency near the optimal region rather than being strictly guided by the maintenance model.

The maintenance frequency obtained from this model (either by using the component's characteristics extracted from data, or by using the desired characteristics) can define the need for on-line maintenance. Simply, if a maintenance interval shorter than the refueling outage interval is needed to satisfy a component's performance, then there is a need to perform some maintenance on-line. Conversely, the model can show that a longer maintenance interval would increase the component's unavailability.

The model also can be used to analyze the contributors to component unavailability. Sensitivity analyses can be undertaken to analyze different maintenance strategies that may reduce the component's unavailability (Reference 1). Maintenance downtime and/or test interval also may need to be reduced to reach a particular unavailability value. In using the results of the maintenance model, maintenance personnel should be consulted to determine if the maintenance downtime can be reduced.

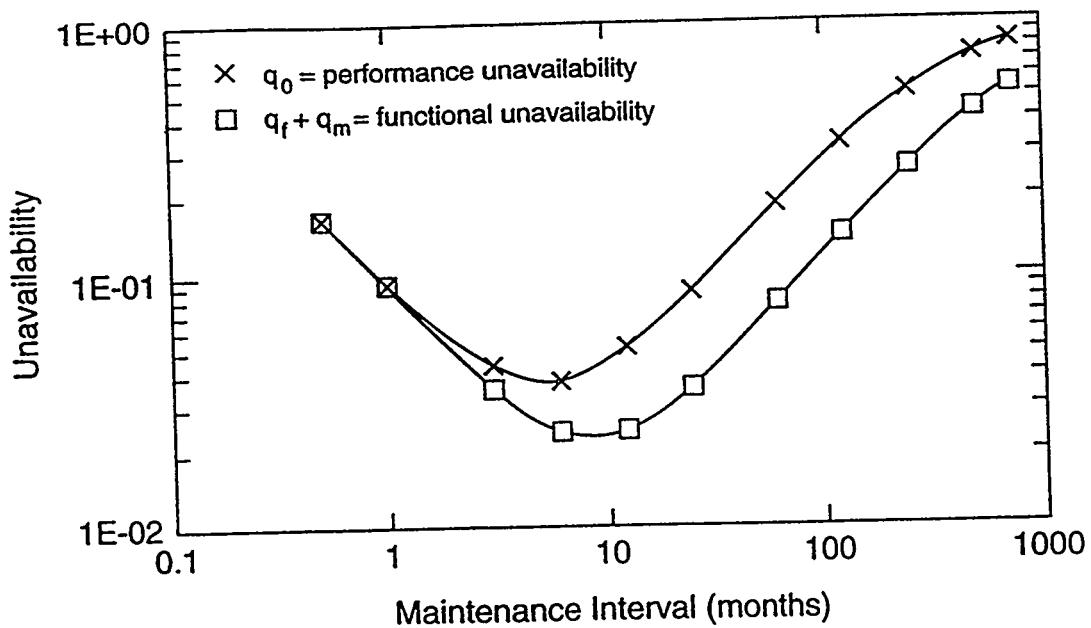


Figure 1 Component performance and functional unavailability as a function of maintenance interval  
 $(\lambda = 10^{-6}/\text{hr}, T = 1 \text{ month, degradation/failure} = 10, \text{repair downtime} = 72 \text{ hrs.,}$   
 $\text{maintenance downtime} = 72 \text{ hrs.})$

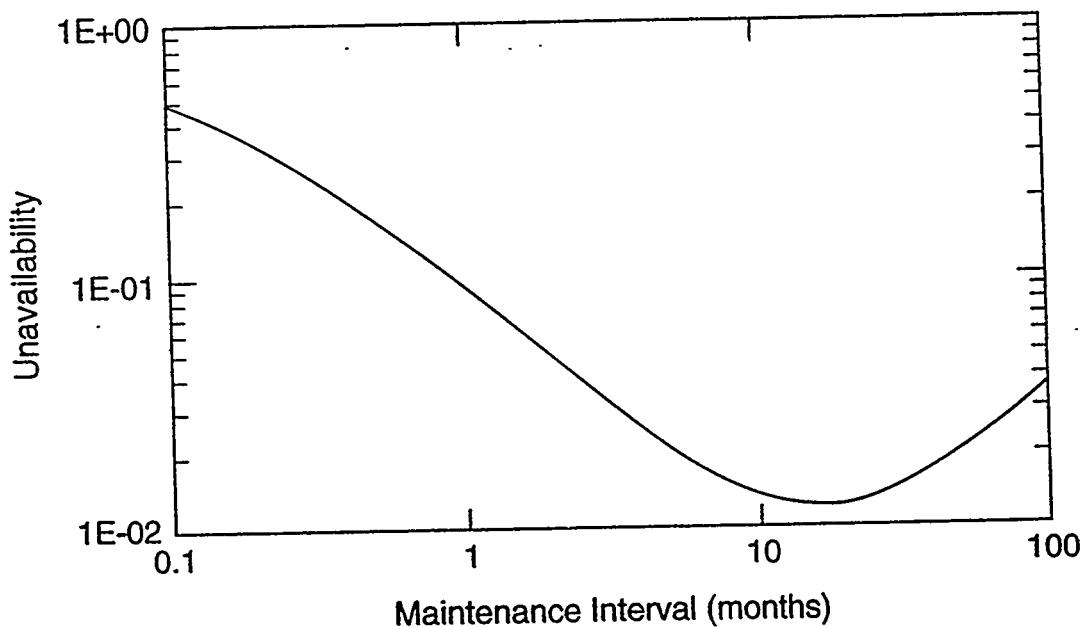


Figure 2 Component functional unavailability versus maintenance interval  
 $(\text{failed unavailability} = 1 \times 10^{-3}, \text{reference maintenance interval} = 3 \text{ months, } T = 1 \text{ month,}$   
 $\text{maintenance downtime} = 72 \text{ hrs., repair downtime} = 72 \text{ hrs.})$

## V. SUMMARY

In this paper, we presented a component-level maintenance model to evaluate the impact of maintenance on a component's performance. This model includes not only the impact of maintenance on the component's downtimes, but also the beneficial aspect of maintenance, in terms of its effects on the component's reliability. We discussed applications and defined uses of the model that balance the beneficial and adverse impacts of maintenance. Using this model will provide a quantitative basis in making decisions on maintenance to achieve desired level of component performance.

## VI. REFERENCES

1. D. Stock, W. Vesely, and P. Samanta, "Development and Application of Degradation Modeling to Define Maintenance Practices," NUREG/CR-5967, BNL-NUREG-52353, June 1994.
2. W. Vesely and J. Rezos, "Risk-Based Maintenance Modeling: Prioritization of Maintenance Importances and Quantification of Maintenance Effectiveness," NUREG/CR-6002, BNL-NUREG-52332, in press.