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GUIDE FOR PRIORITIZING POWER PLANT
PRODUCTIVITY IMPROVEMENT PROJECTS

MODIFICATION AND SIMPLIFICATION OF
THE DOE/MRI METHODOLOGY

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Oak Ridge, Tennessee 37830

Operated by
UNION CARBIDE CORPORATION
for the
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PREFACE

In recent years, the subject of public utility power plant productivity and reliability has received significant attention from both Federal and State agencies and from within the utilities. One study that resulted from this work (1) was an FEA-sponsored program that had as its purpose the development of improved techniques for assessing cause of power plant unavailability. This effort produced quantitative techniques for predicting changes in power plant availability resulting from corrective actions. The results of this study have become widely known as the DOE/MRI methodology for calculating increased power plant equivalent availability resulting from instituting improvement projects.

To further the development of the DOE/MRI methodology for assessing and quantifying the effect of improvement projects, the Department of Energy initiated studies with two states to demonstrate the methodology in operating plants. These studies were focused on applying the methodology to specific power plants (fossil-fueled and nuclear) and on identifying any difficulties in using the method. In the course of these investigations, several problems in applying the DOE/MRI methodology were uncovered. Various recommendations were made for both eliminating the identified deficiencies in the methodology and for simplifying several of the calculations needed to evaluate proposed plant improvements.

The information provided in this report describes four major modifications to the DOE/MRI methodology which eliminate previously uncovered deficiencies and simplify calculational methods. For a detailed discussion of the entire DOE/MRI methodology, reference (1) should be consulted.

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1.0 INTRODUCTION

This report describes modifications to the DOE/MRI methodology to eliminate identified deficiencies and simplify calculations. The four major areas addressed in this report are as follows:

- Modification of Methodology to be Applicable to Concurrent Failures

The methodology in its present form assigns all outages to only a single component, which is a procedure that can result in misleading values for component reliability parameters. This modification is detailed in section 2.0.

- Modification of Methodology to Include Components Which are Repairable Only with a Unit Outage

Currently, the methodology uses reliability equations for systems containing parallel components, which are valid only if the components can be repaired with the unit on-line. Section 3.0 describes this modification.

- Simplification of Methodology Equation for Unit Unavailability Due to Component Loss of Function (U_F)

In its present form, the equation for U_F is difficult to understand and comprehend. The simplification developed for U_F is detailed in section 4.0.

- Modification of Methodology to Account for Details of Outage Duration

Currently, the DOE/MRI methodology uses only a single coefficient to describe a component's outage duration. Thus significant details about the events in an outage repair process are lost. Section 5.0 describes this modification.

For the full details of how these modifications affect the DOE/MRI methodology, reference (1) should be studied along with this report.

2.0 MODIFICATION OF THE DOE/MRI METHODOLOGY TO BE APPLICABLE TO CONCURRENT FAILURES

The DOE/MRI methodology in its present form assumes that all component failures are independent and nonoverlapping. This is equivalent to assuming that one component cannot fail while another component is being repaired. Using this practice, for all full and partial forced outages, only one component is assigned the hours lost by the unit. This approach can result in misleading values of a component's equivalent meantime-to-outage (eM) and equivalent meantime-to-restore (em). When there are large inaccuracies in these coefficients, then the predicted change in unit equivalent availability (ΔEA) for various improvement projects is also inaccurate, and the methodology is of limited usefulness.

This section describes how the methodology can be modified to be applicable to concurrent or multiple failures. Presently, there is no commonly accepted approach in the utility industry for handling multiple failures. This is because there is no consensus among reliability engineers as to the proper way to proportion the outage hours or lost megawatt hours among the simultaneous failed components during a unit outage. There are several approaches that can be used to assign the megawatt hours lost by concurrent failures. The following paragraphs describe various approaches to this problem.

One approach is simply to assign all the unit outage hours to a single failed component. In this situation, the component which either initially caused the outage or has the greatest impact on the unit capacity is assigned the outage hours. This approach reduces all multiple failures to a single failure, greatly simplifying the collection of outage data. Unfortunately, it also gives an inaccurate result with limited usefulness.

Another approach is to proportion the outage hours among the various failed components. In dividing the outage hours, there exist two possible methods to be followed. One possibility is to proportion the outage hours based on the unit capacity loss caused by each failed component. For example, assume that during a given time period a unit had its capacity reduced by 40 MWe due to the failure of two independent components, "A" and "B". Assume that the failure of component A results in a unit derating of 40 MWe, and the failure of component B causes a unit derating of 10 MWe. If these components are assumed independent, the effect of their failure on unit derating is nonadditive. Taking a proportional

approach and assigning outage hours based on the unit capacity loss caused by each failed component, four-fifths $[40/(40+10)]$ of the unit capacity loss is assigned to component A (32 MWe), and one-fifth $[10/(40+10)]$ of the unit capacity loss is assigned to component B (8 MWe).

The second method for proportioning outage hours among various failed components uses the difference in unit capacity loss caused by each failed component. For the above example, component B is assigned the first 10 MWe of unit capacity loss, and component A is given the balance (40 MWe - 10 MWe = 30 MWe).

In either method, the megawatt hours lost attributable to each component is found by multiplying the unit capacity loss associated with the component (MWe) by the outage duration time in hours. As illustrated in the above example, these two different methods for proportioning outage hours generally produce different results.

Before attempting to resolve the above problem, recall the main objective of the DOE/MRI methodology is to predict as accurately as possible the change in power plant productivity for a given improvement project. To meet this objective, it is not necessary to devise a complex calculational weighting scheme to have the methodology handle concurrent failures. Instead, only the data collection and analysis techniques of the methodology need to be modified. It can be shown that concurrent failures can be easily handled, while still retaining the power plant productivity predictive capability of the methodology, by refining the methodology to collect component out-of-full service data for all failed components.

For these reasons, a third approach -- different from the two methods described above -- is used by the methodology to handle concurrent failures. Basically, all out-of-full service events are recorded for the unit's major components over a given period of time. Then with an improvement project defined, the historical component events are modified and a new "hypothetical" component event list developed. This hypothetical component event list is used to construct a new hypothetical unit power profile from the unit's historical power profile over the time period for which component event data has been collected. The differences in the historical and hypothetical power profiles are then used to calculate the change in unit equivalent availability the unit would undergo if the improvement project is implemented at the unit.

An example is presented below to better illustrate the methodology's approach to handle concurrent outages. A unit operates at its maximum dependable capacity (MDC) until time T_1 . At this time, component "A" in the unit is removed from full service, which results in a reduction of the unit power to 80% of its MDC. The unit maintains this power until time T_4 . However, at some time T_2 between T_1 and T_4 , a second component is taken out of full service which, in itself, causes no further decrease in unit power. This event lasts from time T_2 to T_3 . However, if component "A" had not been out-of-full service, component "B" would have resulted in the unit power decreasing to 90% of its MDC. The "historical" power profile of the unit is depicted in Figure 1. The dashed line indicates the power profile the unit would have if component "B" had failed, but not component "A". If the improvement project involved modifying component "A" such that the component "A" outage shown in Figure 1 is eliminated, then the methodology would calculate the ΔEA for this improvement project by assuming the unit would follow the "hypothetical" power profile given by the dashed line. The shaded area in Figure 1 is the additional megawatt hours the unit would obtain by performing this improvement project. If the time period is T_0 over which the unit data is collected, then the ΔEA from the component "A" improvement project is found as follows:

$$\Delta EA_{\text{modified for current events}} = \frac{\text{Additional megawatt hours unit generates as result of improvement project}}{\text{Maximum megawatt hours unit could have generated in time period over which data collected}} \quad (1)$$

Using the unit power level and times shown in Figure 1 gives:

$$\Delta EA_{\text{modified for current events}} = \frac{.2 \text{ MDC } (T_4 - T_1) - .1 \text{ MDC } (T_2 - T_3)}{\text{MDC } (T_0)} \quad (2)$$

or

$$\Delta EA_{\text{modified for current events}} = \frac{.2 (T_4 - T_1) - .1 (T_2 - T_3)}{T_0} \quad (3)$$

POWER PROFILE OF UNIT WITH TWO CONCURRENT EVENTS
IN COMPONENTS "A" AND "B"

Figure 1

It should be noted that if no concurrent outage data had been kept for component "B", the ΔEA predicted by eliminating the component "A" events would be given by:

$$\Delta EA_{\text{no concurrent data}} = \frac{.2 (T_4 - T_1)}{T_0} \quad (4)$$

Comparing equations (3) and (4) gives the change in the ΔEA predicted by modifying the DOE/MRI methodology to handle concurrent failures for this example.

The Δ EA calculated from this approach assumes that a unit's component events are not statistically random, but the time and duration of their occurrence are dependent on an individual unit's operating and maintenance practices. This assumption, while certainly not completely valid, may, in fact, be no worse than the opposite assumption that a power plant's components events can be treated as if they are random events.

A component is defined to be in full service if the component is available for operation with no resultant unit capacity loss. Conversely, a component is defined to be out-of-full service if component operation results in unit capacity loss. Thus, whether a component is in full service or out-of-full service depends on the component's effect on unit capacity if placed in operation, assuming all other components in the unit are fully operational. A component can be operational but out-of-full service. An example of this would be a condenser operating with a significant number of tube leaks, such that a unit capacity reduction is required. A component is not out-of-full service if the unit is shut down and no repair, testing, or maintenance is performed on it. However, if the unit is shut down and any type of work is performed on a component, then the component, for the period over which such work is performed, is declared out-of-full service.

A spare component, not in operation in a system containing parallel components, is considered to be in full service if the component is capable of full operation if needed. However, such a spare component is considered to be out-of-full service while any repair, testing, or maintenance is being performed on the component.

A component's out-of-full service usually includes the time to ramp down the unit to when repair work begins. The component's out-of-full service time also includes the time from when the component is declared back in service to when the unit is brought back on-line and/or the unit is returned to load control. Any number of components in the unit can be in the out-of-full service state. Therefore, the out-of-full service data will provide the methodology with the ability to handle concurrent failures.

It should be understood that the component can be out-of-full service for several reasons, which include:

- Component loss-of-function capability (i.e., mechanical breakdown, rotational or vibrational problem, etc.);
- Component preventive maintenance;
- Component inspection, surveillance, or testing;
- Component repair and/or modification;
- Component operating out-of-spec (i.e., component's speed, temperature, pressure, emissions, etc.).

The reason why the component is brought off-line is important information to record in order to properly evaluate a proposed improvement project using the DOE/MRI methodology.

The present DOE/MRI methodology uses the meantime-to-outage parameter (M_1) for a single component, and equivalent meantime-to-outage parameter (eM) for a system composed of two or more parallel components. For handling concurrent outages using this modified approach, these parameters become meaningless. Therefore, two new corresponding parameters for use in the methodology are proposed:

- Single component meantime-to-out of full service;
- Parallel system's equivalent meantime-to-out of full service.

The meantime-to-out of full service of a single component is the average time a component remains in a full-service state before going into an out-of-full service state. The equivalent meantime-to-out of full service is the average time a system containing parallel components remains in a full service state before going into an out-of-full service state. The relationship between a single component's meantime-to-out of full service and a parallel system's equivalent meantime-to-out of full service is discussed in section 3.0.

In order to simplify subscript notation, this report uses the same symbols to denote meantime-to-out of full service as the DOE/MRI methodology currently uses to denote meantime-to-outage. Therefore, hereafter in this and ensuing work, the following notation will be used:

M_1 = Single component meantime-to-out of full service

eM = System containing parallel components equivalent meantime-to-out of full service

M_1^* = Component meantime-to-outage (referred to as M_1 in DOE/MRI methodology)

eM^* = System containing parallel components equivalent meantime-to-outage (referred to as eM in DOE/MRI methodology).

The duration of a component's out-of-full service time can be composed of many events. It is essential to record these events in order to adequately assess the productivity improvement achievable from components/systems which have been involved in multiple failures. These events and the incorporation of multiple component outage data into the calculation of the DOE/MRI methodology's equivalent meantime-to-restore parameter (eM) is discussed and illustrated in section 5.0.

3.0 MODIFY METHODOLOGY TO INCLUDE COMPONENTS REPAIRABLE ONLY WITH UNIT OUTAGE

This section of the report describes the approach used to modify the methodology to include components repairable only with unit outage. This modification is based on using the single component's meantime-to-out of full service (M_1) and the equivalent meantime-to-out of full service (eM) parameters developed in the previous sections.

The meantime-to-out of full service parameter (M_1) can be related to the component's out-of-full service rate by knowing the probability distribution for the component to be in full service at a given time. Assuming the probability of a component in full service can be expressed by the exponential law, as given in the DOE/MRI methodology(2), the probability a component is in full service at time t is given by:

$$P_1(t) = e^{-\lambda t} \quad (5)$$

where

$$P_1(t) = \text{Probability a single component is in full service at time } t$$

$$\lambda = \text{Component out-of-full service rate, hr}^{-1}$$

The relationship between M_1 and λ is found by integrating $P_1(t)$ over all values of time. This integral also defines the component's meantime-to-out of full service (M_1). Therefore, using equation (5) in this integral gives:

$$M_1 = \int_0^{\infty} P_1(t) dt = \int_0^{\infty} e^{-\lambda t} dt \quad (6)$$

Evaluation of the last integral in equation (6) gives:

$$M_1 = \frac{1}{\lambda} \quad (7)$$

By analogy with the DOE/MRI methodology, the concept of an equivalent meantime-to-out of full service can be derived for a system containing parallel components from its single components meantime-to-out of full service.

The relationship between eM and M_1 for parallel component systems depends on several factors, which include:

- ° Whether parallel components can be repaired with the unit on-line or require unit shutdown;
- ° Degree of component redundancy in system (i.e., number of parallel components versus number required for full power unit operation).

Using the DOE/MRI methodology relationships for a system containing identical parallel components (3), the meantime-to-out of full service can be found as:

$$eM = \frac{\sum_{j=r}^n \binom{n}{j} M_1^j m_1^{n-j}}{n \binom{n-1}{r-1} M_1^{r-1} m_1^{n-r}} \quad (8)$$

where

eM = Equivalent meantime-to-out of full service of parallel component system, hours

M_1 = Meantime-to-out of full service of single component, hours

m_1 = Meantime-to-restore for one of the identical components, hours

n = Total number of parallel components in system

r = Number of components required for full power operation of unit

j = A dummy variable that takes on values of r to n

$$\binom{n}{j} = \frac{n!}{j!(n-j)!}$$

Table 1 gives formulas for eM for different combinations of repairable parallel components/systems using equation (8). Formulas have been developed for parallel component system with total number of components (n) ranging between one and ten and number of components required operational (r) for full power varying from n-3 to n, except when n is less than four (4). When n is less than 4, Table 1 includes formulas for values of r ranging from one (1) to n.

The basis of equation (8) is clearly described in reference D2(4) of the DOE/MRI methodology report as applying only to parallel components that are repairable with the unit on-line. However, there are many power plant parallel components which are only repairable during a full outage. An example of such a system is the reactor recirculation pumps at a boiling water reactor unit. Therefore, for future work equation (8) will only be used for repairable parallel component systems.

The equivalent meantime-to-out of full service must also be developed for a system containing parallel components not repairable with the unit on-line. In this case, it is assumed that the system is composed of n identical repairable components, r of which are needed to be in full service or the unit will suffer a capacity loss. Let $P_1(t)$ denote the probability a single component is in full service at time t. Then the probability a single component is not in full service at time t is given by $[1 - P_1(t)]$. The probability that some particular combination of j components are in full service and n-j components are not in a full service state is:

$$P_1(t)^j [1 - P_1(t)]^{n-j} \quad (9)$$

There are, however,

$$\binom{n}{j} \equiv \frac{n!}{j! (n-j)!}$$

different possible combinations of j components in full service and n-j components not in full service within the

TABLE 1

EQUIVALENT MEANTIME-TO-EVENT FOR COMPONENTS REPAIRABLE

WITH UNIT ON-LINE

[Equation (8)]

 n' = Total number of parallel components. r = Number of components required for unit to maintain its gross dependable capacity.

$n' \backslash r$	1	2	3	4	5	6	7	8	9	10
1	M_1									
2	$M_1 + \frac{M_1^2}{2m}$	$\frac{M_1}{2}$								
3	$M_1 + \frac{M_1^2}{m} + \frac{M_1^3}{3m^2}$	$\frac{M_1}{2} + \frac{M_1^2}{6m}$	$\frac{M_1}{3}$							
4	$M_1 + \frac{3M_1^2}{2m} + \frac{M_1^3}{m^2} + \frac{M_1^4}{4m^3}$	$\frac{M_1^2}{2} + \frac{M_1^3}{3m} + \frac{M_1^4}{12m^2}$	$\frac{M_1}{3} + \frac{M_1^2}{12m}$	$\frac{M_1}{4}$						
5		$\frac{M_1}{2} + \frac{M_1^2}{2m} + \frac{M_1^3}{5m^2} + \frac{M_1^4}{20m^3}$	$\frac{M_1}{3} + \frac{M_1^2}{6m} + \frac{M_1^3}{30m^2}$	$\frac{M_1}{4} + \frac{M_1^2}{20m}$	$\frac{M_1}{5}$					
6			$\frac{M_1}{3} + \frac{M_1^2}{4m} + \frac{M_1^3}{10m^2} + \frac{M_1^4}{60m^3}$	$\frac{M_1}{4} + \frac{M_1^2}{10m} + \frac{M_1^3}{60m^2}$	$\frac{M_1}{5} + \frac{M_1^2}{30m}$	$\frac{M_1}{6}$				
7				$\frac{M_1}{4} + \frac{3M_1^2}{20m} + \frac{M_1^3}{20m^2} + \frac{M_1^4}{140m^3}$	$\frac{M_1}{5} + \frac{M_1^2}{15m} + \frac{M_1^3}{42m^2}$	$\frac{M_1}{6} + \frac{M_1^2}{42m}$	$\frac{M_1}{7}$			
8					$\frac{M_1}{5} + \frac{M_1^2}{10m} + \frac{M_1^3}{35m^2} + \frac{M_1^4}{280m^3}$	$\frac{M_1}{6} + \frac{M_1^2}{21m} + \frac{M_1^3}{168m^2}$	$\frac{M_1}{7} + \frac{M_1^2}{56m}$	$\frac{M_1}{8}$		
9						$\frac{M_1}{6} + \frac{M_1^2}{14m} + \frac{M_1^3}{56m^2} + \frac{M_1^4}{504m^3}$	$\frac{M_1}{7} + \frac{M_1^2}{28m} + \frac{M_1^3}{252m^2}$	$\frac{M_1}{8} + \frac{M_1^2}{72m}$	$\frac{M_1}{9}$	
10							$\frac{M_1}{7} + \frac{3M_1^2}{56m} + \frac{M_1^3}{84m^2} + \frac{M_1^4}{840m^3}$	$\frac{M_1}{8} + \frac{M_1^2}{36m} + \frac{M_1^3}{360m^2}$	$\frac{M_1}{9} + \frac{M_1^2}{90m}$	$\frac{M_1}{10}$

NOT APPLICABLE

Use Equation (8) to find

system. Because each of these combinations is equally probable, the probability that any j components will be in full service at time t is given by:

$$\begin{array}{l} \text{Probability } j \\ \text{components in} \\ \text{full service} \end{array} = \binom{n}{j} P_1(t)^j [1 - P_1(t)]^{n-j} \quad (10)$$

If the system requires r components to be in full service for full unit power, then the probability the system is not causing a unit outage at any time t is obtained by summing equation (10) for all values of j between r and n .

Therefore,

$$P(t) = \sum_{j=r}^n \binom{n}{j} P_1(t)^j [1 - P_1(t)]^{n-j} \quad (11)$$

where

$$P(t) = \begin{array}{l} \text{Probability system is in full service at} \\ \text{time } t \end{array}$$

The system's equivalent meantime-to-out of full service is found by integrating equation (11) over all possible values of time. Therefore,

$$eM = \sum_{j=r}^n \binom{n}{j} \int_0^{\infty} P_1(t)^j [1 - P_1(t)]^{n-j} dt \quad (12)$$

Substituting the exponential law, which is given by equation (5), for $P_1(t)$ into equation (12) gives:

$$eM = \sum_{j=r}^n \binom{n}{j} \int_0^{\infty} [e^{-\lambda t}]^j [1 - e^{-\lambda t}]^{n-j} dt \quad (13)$$

Define the variable u as follows:

$$u = e^{-\lambda t} \quad (14)$$

Taking the derivative of u in equation (14) gives:

$$du = -\lambda e^{-\lambda t} dt \quad (15)$$

Substituting equations (14) and (15) into the integrand of equation (12) and changing the limits on the integral gives:

$$eM = \frac{1}{\lambda} \sum_{j=r}^n \binom{n}{j} \int_0^1 u^{j-1} (1-u)^{n-j} du \quad (16)$$

The integral in equation (15) is recognized as the Beta function, which can be expressed as:

$$\int_0^1 u^{j-1} (1-u)^{n-j} du = B(j, n-j+1) \quad (17)$$

where

$B(j, n-j+1)$ is the Beta function, which is given by:

$$B(j, n-j+1) = \frac{(j-1)! (n-j)!}{n!} \quad (18)$$

The Beta function is a mathematical function whose values are found in mathematical handbook references (5) (6).

Putting equations (17) and (18) and the definition of $\binom{n}{j}$ into equation (16) gives:

$$eM = M_1 \sum_{j=r}^n \frac{(j-1)!}{j!} \quad (19)$$

Equation (19) is valid to compute the equivalent meantime-to-out of full service (eM) for parallel component systems repairable only with unit outage.

Table 2 gives formulas for different combinations of non-repairable systems with parallel components using equation (19). Formulas have been developed for systems with the total number of parallel components (n) ranging between one and ten, and the number of components needed for full power unit operation (r), less than or equal to n.

For a single component, the DOE/MRI methodology calculates the equivalent meantime-to-restore⁽⁷⁾ (em_1) by weighting the component's meantime-to-restore coefficient by the fraction of full unit power lost due to an outage. Therefore, em_1 is given by:

$$em_1 = m_1 \left(\frac{\overline{CL}}{MDC} \right) \quad (20)$$

where

em_1 = Equivalent meantime-to-restore for single component, hours

m_1 = Time-to-restore coefficient for single component, hours

$\overline{CL}$ = Average unit capacity loss due to outages caused by component failures, MWe

MDC = Unit maximum dependable capacity, MWe

For systems with parallel components, the current DOE/MRI methodology calculates the system's equivalent meantime-to-restore⁽⁸⁾ as:

$$em = \frac{\sum_{j=0}^{r-1} \binom{n}{j} M_1^j em_1^{n-j}}{n \binom{n-1}{r-1} M_1^{r-1} em_1^{n-r}} \quad (21)$$

TABLE 2

EQUIVALENT MEANTIME-TO-OUT OF FULL SERVICE
FOR COMPONENTS REPAIRABLE ONLY WITH UNIT OUTAGE
[Equation (19)]

n = Total number of parallel components operating

r = Number of components required for full operation

$\begin{smallmatrix} r \\ n \end{smallmatrix}$	1	2	3	4	5	6	7	8	9	10
1	M_1									
2	$\frac{3}{2} M_1$	$\frac{1}{2} M_1$								
3	$\frac{11}{6} M_1$	$\frac{5}{6} M_1$	$\frac{1}{3} M_1$							
4	$\frac{25}{12} M_1$	$\frac{13}{12} M_1$	$\frac{7}{12} M_1$	$\frac{1}{4} M_1$						
5	$\frac{137}{60} M_1$	$\frac{77}{60} M_1$	$\frac{47}{60} M_1$	$\frac{9}{20} M_1$	$\frac{1}{5} M_1$					
6	$\frac{49}{20} M_1$	$\frac{29}{20} M_1$	$\frac{19}{20} M_1$	$\frac{37}{60} M_1$	$\frac{11}{30} M_1$	$\frac{1}{6} M_1$				
7	$\frac{363}{140} M_1$	$\frac{223}{140} M_1$	$\frac{153}{140} M_1$	$\frac{319}{420} M_1$	$\frac{107}{210} M_1$	$\frac{13}{42} M_1$	$\frac{1}{7} M_1$			
8	$\frac{761}{280} M_1$	$\frac{481}{280} M_1$	$\frac{341}{280} M_1$	$\frac{743}{840} M_1$	$\frac{533}{840} M_1$	$\frac{73}{168} M_1$	$\frac{15}{56} M_1$	$\frac{1}{8} M_1$		
9	$\frac{7129}{2520} M_1$	$\frac{4609}{2520} M_1$	$\frac{3349}{2520} M_1$	$\frac{2509}{2520} M_1$	$\frac{1879}{2520} M_1$	$\frac{275}{504} M_1$	$\frac{191}{504} M_1$	$\frac{119}{504} M_1$	$\frac{1}{9} M_1$	
10	$\frac{7381}{2520} M_1$	$\frac{4861}{2520} M_1$	$\frac{3601}{2520} M_1$	$\frac{2761}{2520} M_1$	$\frac{2131}{2520} M_1$	$\frac{1627}{2520} M_1$	$\frac{1207}{2520} M_1$	$\frac{121}{360} M_1$	$\frac{133}{630} M_1$	$\frac{1}{10} M_1$

where

M_1^* = Component meantime-to-outage, hours

n = Total number of parallel components

r = Number of components required for full operation

j = A dummy variable that takes on values of r to n

$$\binom{n}{j} = \frac{n!}{j!(n-j)!}$$

The justification for equation (21) is given in reference D2 of the DOE/MRI methodology(9), in which equation (21) is described as being valid only for repairable parallel components. Equation (21) is unnecessarily complicated for use in power plant applications. Equation (20) is valid for calculating the equivalent meantime-to-restore for systems with either repairable or nonrepairable parallel components. Therefore, equation (20) should be used in the methodology to replace equation (21) and for application to both repairable and nonrepairable components. This approach further simplifies the methodology and, consequently, will increase the ease of its application.

4.0 SIMPLIFY EQUATION FOR UNAVAILABILITY DUE TO LOSS OF FUNCTION

The DOE/MRI methodology equation for the component unavailability due to loss of function is difficult to understand and comprehend. An alternate form for the calculation of U_F has been found which is simpler and contains more direct physical meaning. In this section, a derivation of this alternate form starting with the current methodology equation to calculate U_F is presented. The notation adopted in this section is the same as that used in the DOE/MRI methodology⁽¹⁰⁾, except for the variable "eM" which is expressed as eM^* . This exception has been adopted in order to be consistent with the notational designation for eM throughout this report.

The following expression is used for the U_F calculation for a unit whose functional representation has been reduced to series elements in the DOE/MRI methodology⁽¹¹⁾:

$$U_F = \left[1 - \frac{1}{1 + \left(\frac{em}{eM^*} \right) K} \right] K_T \quad (22)$$

where

$\left(\frac{em}{eM^*} \right)$ is the summation of $\left(\frac{em}{eM^*} \right)$ for all series elements in the unit

$$K = \frac{1}{\left(1 - \frac{m'}{M'} \right)}$$

$$K_T = 1 - \frac{T_p}{T} - \frac{T_c}{T}$$

- m' = Meantime-to-restore for partial outages, hours
- M' = Meantime-to-outage of partial outages, hours
- T = Period, hours
- T_C = Total full power outage hours due to conditional events
- T_P = Total full power outage hours due to administrative events

Equation (22) can be simplified so the factors K and K_T are eliminated.

DERIVATION OF U_F EQUATION WITHOUT K AND K_T COEFFICIENTS

Let

- T_F = Full power outage time due to loss of function, hours
- T_F' = Equivalent full power outage time due to partial load reduction caused from loss of function, hours
- T_O = Unit operational time (at full and reduced load), hours
- T = Period hours
- m = Meantime-to-restore, hours
- M = Meantime-to-outage of full outages, hours
- m' = Meantime-to-restore for partial outages, hours
- M' = Meantime-to-outage of partial outages, hours

The unit unavailability due to loss of function is given by:

$$U_F = \frac{T_F + T_F'}{T} \quad (23)$$

Assuming, as in the DOE/MRI methodology⁽¹²⁾, that outage times are proportional to unit operational times, then T_F and T_F' can be expressed as:

$$T_F = \left(\frac{m}{M} \right) T_O \quad (24)$$

$$T_F' = \left(\frac{m'}{M'} \right) T_O \quad (25)$$

Substituting equations (24) and (25) into equation (23) gives:

$$U_F = \frac{\left(\frac{m}{M} T_O \right) + \left(\frac{m'}{M'} T_O \right)}{T} \quad (26)$$

Equation (26) can be rewritten as:

$$U_F = \left(\frac{m}{M} + \frac{m'}{M'} \right) \frac{T_O}{T} \quad (27)$$

Using the following definition given in the DOE/MRI methodology⁽¹³⁾:

$$\left(\frac{em}{eM^*} \right) = \left(\frac{m}{M} + \frac{m'}{M'} \right) \quad (28)$$

and substituting equation (28) into (27) yields a simplified equation for U_F , which is given by:

$$U_F = \left(\frac{em}{eM^*} \right) \frac{T_O}{T} \quad (29)$$

Equation (29) yields the same unit U_F as equation (22), but it is much simpler to apply since the K and K_T coefficients have been eliminated.

COMPARISON OF EQUATIONS (22) AND (29) TO EXAMPLE GIVEN IN
MRI METHODOLOGY REPORT

Applying equation (22) to the example given in Appendix A of the DOE/MRI methodology⁽¹⁴⁾ gives U_F equal to .0185. Using data from this example on page A-18, it is shown that:

$$\left(\frac{em}{eM^*} \right) = \frac{185}{9000} \quad (30)$$

In addition, the unit operation time is given as 9,000 hours and the period as 10,000 hours on page A-15 of the same example.

Thus, in this example the unit availability is given by:

$$\frac{T_O}{T} = \frac{9000}{10000} = .9 \quad (31)$$

Combining equations (30) and (31) and substituting into equation (29) gives:

$$U_F = \left(\frac{em}{eM^*} \right) \frac{T_O}{T} = \left(\frac{185}{9000} \right) (.9) = .0185 \quad (32)$$

With the data given in the DOE/MRI methodology, the same unit U_F is computed using equation (29) as equation (22).

The equivalent meantime-to-out of full service (eM) parameter described in section 2.0 can be substituted into equation (29) for eM^* . This substitution yields the equation:

$$U_F = \left(\frac{em}{eM} \right) \frac{T_O}{T} \quad (33)$$

PHYSICAL INTERPRETATION OF EQUATION (33)

The physical interpretation of the right-hand side of equation (33) is important to understand when applying the methodology to evaluate an improvement project. The remaining paragraphs in this section develop this physical interpretation.

The physical interpretation of e_m and e_M are as follows:

$$e_m = \frac{\left(\begin{array}{c} \text{MWH lost by components in out-of-} \\ \text{full service state} \end{array} \right)}{\left(\begin{array}{c} \text{Number of times} \\ \text{component brought} \\ \text{out of full service} \end{array} \right) \left(\begin{array}{c} \text{Unit Maximum} \\ \text{Dependable} \\ \text{Capacity, MWe} \end{array} \right)} \quad (34)$$

$$e_M = \frac{\left(\begin{array}{c} \text{Unit operational time, hours} \end{array} \right)}{\left(\begin{array}{c} \text{Number of times component} \\ \text{brought out-of-full service} \end{array} \right)} \quad (35)$$

Dividing equation (34) by equation (35) gives:

$$\left(\frac{e_m}{e_M} \right) = \frac{\left(\begin{array}{c} \text{MWH lost by components in out-of-} \\ \text{full service state} \end{array} \right)}{\left(\begin{array}{c} \text{Unit operational} \\ \text{time, hours} \end{array} \right) \left(\begin{array}{c} \text{Unit Maximum} \\ \text{Dependable} \\ \text{Capacity, MWe} \end{array} \right)} \quad (36)$$

Multiplying equation (36) by the unit availability $\frac{T_o}{T}$ yields the result:

$$U_F = \left(\frac{e_m}{e_M} \right) \frac{T_o}{T} = \frac{\left(\begin{array}{c} \text{MWH lost by components in} \\ \text{out-of-full service state} \end{array} \right)}{\left(\begin{array}{c} \text{Period hours} \end{array} \right) \left(\begin{array}{c} \text{Unit Maximum} \\ \text{Dependable} \\ \text{Capacity, MWe} \end{array} \right)}$$

$$= \frac{\left(\begin{array}{c} \text{MWH lost by components in out-} \\ \text{of-full service state} \end{array} \right)}{\left(\begin{array}{c} \text{Maximum possible MWH hours unit} \\ \text{could generate in time period T} \end{array} \right)}$$

$$= \text{Unit unavailability due to components in out-of full service state during time period T} \quad (37)$$

The ratio $[(e_m/e_M) T_o/T]$ is the component's out-of-full service contribution to unit unavailability. If this ratio is 0, then it means the unit loses no MWH in a given period because of components out-of-full service. If this ratio is .5, then it means the unit loses half of the maximum possible MWH it could generate in a given period because of components out-of-full service.

The ratio $[(e_m/e_M) T_o/T]$ can be calculated for each component in the unit. In this manner, one can quantify the contribution of each component to the unit unavailability. This component ratio is useful when evaluating improvement actions. A project will increase the unit's availability if the component's $[(e_m/e_M) T_o/T]$ ratio is decreased following an improvement action.

CONCLUSION

It has been shown in this section that the DOE/MRI methodology equation for component loss of function can be simplified with no loss of accuracy by the use of equation (33) instead of equation (22). Further, equation (33) contains factors whose physical interpretation can be directly related to the unit's productivity.

5.0 MODIFY METHODOLOGY TO ACCOUNT FOR DETAILS AT OUTAGE DURATION

The DOE/MRI methodology uses only a single coefficient to describe the repair of equipment during an outage (i.e., meantime-to-restore coefficient, em). Factors which significantly influence this parameter, such as individual events that constitute a given component repair, are not accounted for by the present methodology, making it difficult to perform a realistic assessment for various improvement projects. Further, different plants have different ways of reporting repair time. Some report the time as the total time from removal or derate of the unit until restoration to full load (breaker to breaker), irrespective of power demand for the unit by load control. Others report repair time as only the time needed to physically repair the equipment, not including any cool-down or start-up transients.

If a realistic assessment of improvement projects is to be obtained, the meantime-to-restore must be subdivided into several factors that influence the outage duration length; namely:

- ° The equivalent time to remove equipment from service and cool it down or otherwise make it ready so that a repair can begin (em_1);
- ° The equivalent time spent waiting for parts, tools, or materials needed to make the repair, or some other delay while working on the component (em_2);
- ° The equivalent time to physically repair the equipment by a work crew (em_3).

The meantime-to-restore a failed component is the sum of the above actions (accounting for parallel activities) that go into making the repair and restoring the equipment to service. For the case of no parallel activities, the meantime-to-restore is simply given by:

$$em = em_1 + em_2 + em_3 \quad (38)$$

Obviously, parallel actions must be treated in such a manner that the calculated time does not exceed the total time to

restore the equipment to service. To assure this result and to properly proportion the outage times to the most significant events, assignment of outage duration times on a chronological event basis is recommended. That is -- the first event is assigned its total time, with the subsequent events being assigned no overlapping times in a chronological order. This concept is best understood by the example shown in Figure 2,

Equipment Cool-Down Time = 3 Hours
 Spare Parts Wait Time = 2 Hours
 Equipment Repair Time = 3 Hours

Figure 2

As shown in this figure, an equipment failure results in a three-hour cool-down period, a two-hour wait time for spare parts, and a three-hour repair time prior to return-to-service of the plant. However, one hour of the wait for spare parts is performed during cool-down, and one hour of the repair is done during the wait for spare parts. If one simply added the times and did not account for parallel activities, an em of eight hours would be reported. By the assignment of non-overlapping times in chronological order, the em is calculated as follows:

Equipment Cool-Down Time = 3 Hours

Spare Parts Wait Time = 1 Hour

Equipment Repair Time = 2 Hours

for a total outage time of six hours.

Additionally, each of the above activities is dependent on many factors. For example, the time to repair the equipment by a work crew depends on several variables, such as:

- Work crew size;
- Utilization of multishift maintenance in repair;
- Vendor support;
- Availability of a repair facility, if needed;
- Labor practices at the plant;
- Effectiveness of repair procedures.

The above list includes some of the factors that could delay the repair of the equipment and the restoration of the plant to full service. Equipment is normally repaired on an orderly and rapid basis, but outage repair delays do occur and must be recorded by the data collection system.

Any event that delays repair should be reported by a cause code so that improvement projects dealing with such things as improved labor practices can be evaluated by the methodology.

The development of a detailed data collection system is paramount in performing analysis of improvement projects. This data collection system must account for all the pieces of an outage and parallel events, as well as other variables that influence the repair duration.

Although such detailed data reporting must appear ambitious, if improvement projects are to be accurately evaluated, information at this level of detail is mandatory. For example, a packing repair to a pump may result in a three-day outage due to lack of a packing at the plant instead of a two-hour outage if the packing were available. A realistic plant improvement project would not necessarily be to

add a redundant pump, but simply to improve the inventory of spare parts at the plant. Only with detailed outage data collection can such conclusions be reached for the improvement projects to be studied using this methodology.

REFERENCES

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- (11) *Ibid*, Vol. II, p. A-8.
- (12) *Ibid*, p. A-8.
- (13) *Ibid*, p. A-10.
- (14) *Ibid*, p. A-14.

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