

## COMPONENT FAILURE MODEL DEPENDENT ON TIME AND CAUSES

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This paper presents a failure model in which the failure rate is a function of cause, of severity of cause, of cause acting duration, and of failure mode. This model was constructed in order to treat the effects of an extreme environmental condition and the common mode failure on system reliability.

Causes were classified into two types and failure modes in three types. The expressions of failure probabilities were obtained for combinations of these cause and failure mode types. This model was compared with failure data. The time dependence was well expressed by the  $\alpha$ th power of time. The values of  $\alpha$  were obtained in the range from 0 to 8.

### 1. Introduction

In a reliability analysis of a complex system such as a nuclear power plant, there still exist many problems which are not clearly solved. The following are among these problems: the adequate treatment of the common mode failure, the secondary failure, and the effect of a extreme environmental condition or accident condition.

The importance of common mode failure has been discussed in the Reactor Safety Study (WASH-1400) [1]. In the Safety Study, the bounding technique was used to evaluate common mode failure. In an effort to obtain more realistic common mode assessment, Fleming [2] has introduced the Beta Factor method, and it was used extensively in the HTGR risk assessment study. The safety study has discussed the effect of an extreme environmental condition. The authors have also pointed out the importance of this effect and have analysed the reliability of a safety system under various accident conditions [3].

Many other studies [4,5,6] on these problems have been performed, but at the present time, there is no definite solution. In this paper, a failure probability model is proposed. In this model, a failure rate is considered as a conditional failure rate, which is a function of cause for a failure, of severity of cause, of cause acting duration, and of failure mode. The common mode failure, the secondary failure, and the failure under extreme condition, can be considered as a statistically independent failure under specific condition. This conditional failure probability is obtained by the pro-

posed failure model. This is a quite straightforward method to treat the above problems.

The basic concept of this model is explained and the expressions of failure probabilities are obtained. The comparisons between this model and failure data are also performed.

### 2. Basic concept

Many failure data [7] of nuclear power plant components have been accumulated under the ordinary operating condition. These failure rates are considered to be constant, and the causes for a failure are not explicitly considered. This constant failure rate is adequate and practical to the rough estimation of a system reliability. But the constant failure rate means that the failure possibility always exists, even immediately after the installation of a new component.

Strictly speaking, a failure is produced by a cause, that is, no failure occurs without cause. It becomes therefore very difficult to treat the common mode failure, the secondary failure, and the effect of an extreme environmental condition, as far as the constant failure rate is used. Hence, the author proposes a failure model, in which the failure rate is not a constant value, but a function of cause, of severity of cause, of cause acting duration, and of failure mode. This is expressed in the equation:

$$\text{Failure rate} = F(C, S, t, M), \quad (1)$$

where  $C$ ,  $S$ ,  $t$ ,  $M$  are cause, severity, cause acting duration, and failure mode, respectively. The demand probability is also expressed in the same form as eq. (1).

### 3. Classification of causes

There are many possible causes for failures. The following twenty causes are selected as fundamental and basic causes to produce a component failure. They are selected not to overlap one another. These causes are impact, vibration, pressure, grit, moisture, stress, temperature, electromagnetic interface, conducting medium, out of tolerance voltage, out of tolerance current, corrosion (acid), corrosion (oxidation), other chemical reactions, calibration, installation, maintenance, operator or operation, test procedure, and manufacturer.

These causes are classified into two types. The first type is impact type and the second is continuous type.

The impact type cause acts in a moment or during a very short time duration such as an impact. This is denoted by  $C = 0$  in this paper. The causes: impact, out of tolerance voltage, out of tolerance current, calibration, installation, maintenance, operator or operation, test procedure, and manufacturer, belong to this type.

The continuous type cause acts on a component continuously during a certain time duration. If this time duration is very short, the effect on a failure is negligibly small. This type is denoted by  $C = 1$ . The continuous type causes are vibration, pressure, grit, moisture, stress, temperature, electromagnetic interface, conducting medium, corrosion (acid, oxidation), and other chemical reactions.

For continuous type cause,  $t$  is the time duration during which a cause is acting on a component. For impact type cause,  $t$  is the time when a failure is observed.

### 4. Severity of a cause

Many causes are considered for one failure mode as listed up in the previous section. For one specific cause, the effect on failure depends greatly on the degree of the cause. Degrees are expressed in various units corresponding to the causes, for example,  $\text{kg}/\text{cm}^2$  for pressure,  $\text{kg m}/\text{h}^2$  for impact, pH for acid, V for voltage, A for current.

For the simplicity of the expression of cause degrees, they are divided into five stages from the normal operating condition to the most severe condition which will be experienced. The values from 1 to 5 are assigned to

severity  $S$ . A severity  $S = 1$  means that the component is exposed to the normal operating condition with regard to the corresponding cause. On the other hand,  $S = 5$  means that a cause acts on the component in the most severe condition.

Under normal operating conditions, it is assumed that only the continuous causes exist and that there is no impact type cause. Then the following relation always holds:

$$F(C = 0, S = 1, t, M) = 0. \quad (2)$$

### 5. Causes and failure modes

In reliability theory, failure rates or probabilities are distinguished into three types: demand probability, operating failure rate and stand-by failure rate. This distinction is determined by failure modes. Then failure modes can be classified into three types corresponding to the failure rate or probability. In this paper, the types of failure modes are expressed by the terminologies "demand type failure mode", "operating type failure mode", and "stand-by type failure mode". They are denoted by  $M = 0$ ,  $M = 1$ ,  $M = 2$ , respectively.

There are two types of causes and three types of failure modes. Therefore, there are six combinations between causes and failure modes.

For the combination of an impact type cause and a demand type failure mode, that is,  $C = 0$  and  $M = 0$ , the failure mechanism is considered as follows. A certain number of components becomes in a failed state at the instant that the impact type cause acts on the components. The failed component will fail to operate upon demand. The component which did not fail by this cause is in the normal state and will operate upon demand. The demand probability increases stepwise when an impact type cause acts on a component and after that the demand probability remains constant unless the further impact type cause acts on it.

In the case of  $C = 0$  and  $M = 1$  or 2, the following failure mechanism is assumed. A certain number of components have a large failure rate when an impact type cause acts on the components. The component having a large failure rate turns into a failed state in accordance with the operation. The component which was not affected by this cause, is in the normal state during the operation.

For a continuous type cause  $C = 1$ , the failure rate of a component continues to increase during a cause acting duration. This is held for the combination of any type of failure mode and a continuous type cause.

6. Failure probability

Component failure probabilities are required for the calculation of system reliability. In this section, the expressions of failure probabilities are obtained.

A failure probability is determined by a failure rate  $F$ , operating time duration  $t_o$ , and stand-by time duration  $t_s$ . To simplify the analysis, the time durations  $t_o$  and  $t_s$  are assumed to be constant and aligned as shown in fig. 1. A demand is required at the beginning of the operation. An impact type cause acts at some point during stand-by time duration, and a continuous type cause begins to act during stand-by time duration and continues to the end of the operation.

In the case of  $C = 0$  and  $M = 0$ , the failure probability is defined as follows:

Failure probability  

$$= 1.0 - \exp(-f(C = 0, S > 1, t, M)), \quad (3)$$

where  $f$  is a function of  $C, S, t, M$ . This expression assures that a failure probability never exceed unity and has the same form as eq. (11) which is the expression of the failure probability for  $C = 1$  and  $M = 0$ .  $f$  is a non-dimensional number. If  $f$  has a small value, the failure probability approximately equals to  $f$  itself, then  $f$  equals to  $F$ : demand probability.

If more than one impact type causes act during a stand-by time duration, the failure probability becomes:

Failure probability  

$$= 1.0 - \exp\left[-\sum_i f_i(C = 0, S > 1, t, M)\right]. \quad (4)$$

In the case of  $C = 0$  and  $M = 1$  or  $2$ , a certain part of the components is affected by the impact type cause and receives a latent damage. It does not fail immediately after the cause, but it ends up having a failure rate  $\lambda_i$ . This part is defined as follows:

$$1.0 - \exp[-f(C = 0, S > 1, t, M)]. \quad (5)$$

It is identical with eq. (3): the expression of the failure probability for  $C = 0$  and  $M = 0$ . The number of components  $N(t)$  which received a latent damage and are

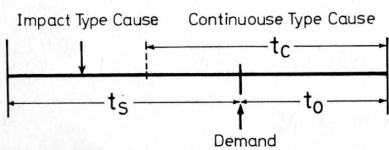


Fig. 1. The arrangement of causes, stand-by time, operating time and demand.

still operative, is governed by the equation:

$$\frac{dN(t)}{dt} = -\lambda_i N(t), \quad (6)$$

where  $\lambda_i$  is the failure rate which expresses the latent damage, and is determined by the cause, the severity of cause, and the failure mode. Then the failure probability of the damaged component becomes:

$$1.0 - \exp(-\lambda_i t), \quad (7)$$

where  $t$  is the time duration after the action of impact type cause ( $M = 2$ ) or after the initiation of operation ( $M = 1$ ).

Therefore the failure probability of the component at the end of the operation is expressed by the next equation:

Failure probability  

$$= [1.0 - \exp(-f(C = 0, S > 1, t_o + t_s, M))] \times [1.0 - \exp(-\lambda_i t)], \quad (8)$$

where  $t = t_o$  for  $M = 1$ , and  $t = t_c$  for  $M = 2$ . The above equation can express the following situation. If the failure rate  $\lambda_i$  is very large, a certain number of components will fail soon after the cause, and the failure probability is identical with that in the case of  $C = 0$  and  $M = 0$ . On the other hand, if  $\lambda_i$  is small, the components can be operated immediately after the cause, and failures increase gradually with the operation or stand-by time of the component. The failure probability has then an upper limit expressed by eq. (5).

The failure rate  $\lambda_i$  has a dimension  $[1/h]$  and  $f$  is a non-dimensional number.

For the continuous type cause,  $C = 1$ , the failure rate or demand probability  $F$  usually increases with the cause acting duration  $t_c$ . In this case the variable  $t$  represents the time duration during which the cause acts on the component. Under normal operating conditions, all the continuous type causes always exist throughout the stand-by and operating time durations. If a cause of  $S = 1$  has no effect on the failure mode  $M$ , the value of  $F$  becomes zero:

$$F(C = 1, S = 1, t, M) = 0. \quad (9)$$

If a cause of  $S > 1$  acts on a component, the failure rate becomes greater than the failure rate under normal conditions. This increased failure rate is considered as the summation of the failure rate under normal operating conditions and the increased part:

Failure rate =  $F(C = 1, S = 1, t, M)$   

$$+ F(C = 1, S > 1, t, M), \quad (10)$$

where  $F(C = 1, S > 1, t, M)$  expresses the increased part of the failure rate. The demand probability for  $C = 1$  is also expressed by the same equation.

Now consider the failure probability of a component in the case of  $C = 1$  and  $M = 0$ . A cause of  $S = 1$  acts on the component throughout the stand-by time duration, and a cause of  $S > 1$  begins to act at a certain point during the stand-by time duration as shown in fig. 1. The failure probability at the beginning of the operation is defined as follows:

Failure probability

$$= 1.0 - \exp[-f(C = 1, S = 1, t_s, M = 0) - f(C = 1, S > 1, t_c - t_o, M = 0)], \quad (11)$$

where  $f$  is a function determined by  $C, S, t, M$ . If  $f \ll 1$ , eq. (11) becomes,

Failure probability

$$= f(C = 1, S = 1, t_s, M = 0) + f(C = 1, S > 1, t_c - t_o, M = 0). \quad (12)$$

In this case,  $f$  equals to the failure probability, that is,  $f = F$ .

Eq. (11) is chosen for the failure probability and not eq. (12) because of the following reason. It is assumed that the failure rate is a function of  $t$ , then  $f$  too has to be a function of  $t$ . If a simple form, such as  $t^\alpha$ , is assumed for the expression of this time dependence,  $f$  will become larger than 1 for very large values of  $t$ . Therefore, eq. (12) is not adequate for the expression of the failure probability because the failure probability becomes larger than 1 for large values of  $t$ . On the other hand, eq. (11) assures that the failure probability is less than 1 for any value of  $t$ . This is the reason that eq. (11) is chosen for the expression of the failure probability.  $f$  is also non-dimensional.

In the case of  $C = 1$  and  $M = 1$ , a failure of component begins to occur after the initiation of operation. The number of normal components  $N(t)$  is governed by the equation:

$$\frac{dN(t)}{dt} = - (f(C = 1, S = 1, t + t_s, M = 1) + f(C = 1, S > 1, t + t_c - t_o, M = 1))N(t), \quad (13)$$

where  $f$  is the failure rate and exactly identical with  $F$ , and  $t$  is the time after the initiation of operation.

Integrating eq. (13),  $N(t)$  is obtained as follows:

$$N(t) = N(0) \exp \left[ - \int_0^t [f(C = 1, S = 1, t + t_s, M = 1) + f(C = 1, S > 1, t + t_c - t_o, M = 1)] dt \right]. \quad (14)$$

If we define

$$f(C = 1, S, t \leq 0, M) = 0.0. \quad (15)$$

eq. (14) is applicable to the case where a cause begins to act after the initiation of operation.

From eq. (14), the failure probability at the end of the operating time duration is derived as follows:

Failure probability

$$= 1.0 - \exp \left[ - \int_0^{t_o} f(C = 1, S = 1, t + t_s, M = 1) dt - \int_0^{t_o} f(C = 1, S > 1, t + t_c - t_o, M = 1) dt \right]. \quad (16)$$

The approximate form for small values of  $f$  is:

Failure probability

$$= \int_0^{t_o} f(C = 1, S = 1, t + t_s, M = 1) dt + \int_0^{t_o} f(C = 1, S > 1, t + t_c - t_o, M = 1) dt. \quad (17)$$

The dimension of  $f$  is known to be  $[1/h]$  from the above equation.

In the case of  $C = 1$  and  $M = 2$ , the failure probability at the end of operation becomes:

Failure probability

$$= 1.0 - \exp \left[ - \int_0^{t_s + t_o} f(C = 1, S = 1, t, M = 2) dt - \int_0^{t_c} f(C = 1, S > 1, t, M = 2) dt \right]. \quad (18)$$

The derivation of this equation is similar to that of eq. (16). The approximate form for small values of  $f$  is:

Failure probability

$$= \int_0^{t_s + t_o} f(C = 1, S = 1, t, M = 2) dt + \int_0^{t_c} f(C = 1, S > 1, t, M = 2) dt. \quad (19)$$

The dimensions of  $f$  is  $[1/h]$ .

The results for all the combinations of  $C$  and  $M$  are presented in table 1.

The time dependence of the function  $f$  is now as-

Table 1  
Failure probabilities at the beginning (for  $M = 0$ ) or end (for  $M = 1, 2$ ) of operating time duration

Cause type $C$	Failure mode type $M$	Failure probability	Approximate form	Dimension of function $f$
0	0	$1.0 - \exp(-f(C, S > 1, t, M))$	$f(C, S > 1, t, M)$	[-]
0	1, 2	$[1.0 - \exp(-f(C, S > 1, t, M))][1.0 - \exp(-\lambda_s t_{o,s})]$	$f(C, S > 1, t, M)\lambda_s t_{o,s}$	[-]
1	0	$1.0 - \exp[-f(C, S = 1, t_s, M) - f(C, S > 1, t_c - t_o, M)]$	$f(C, S = 1, t_s, M) + f(C, S > 1, t_c - t_o, M)$	[-]
1	1	$1.0 - \exp[-\int_0^{t_o} f(C, S = 1, t + t_s, M) + f(C, S > 1, t + t_c - t_o, M) dt]$	$\int_0^{t_o} (f(C, S = 1, t + t_s, M) + f(C, S > 1, t + t_c - t_o, M)) dt$	[1/h]
1	2	$1.0 - \exp[-\int_0^{t_o+t_s} f(C, S = 1, t, M) dt - \int_0^{t_c} f(C, S > 1, t, M) dt]$	$\int_0^{t_o+t_s} f(C, S = 1, t, M) dt + \int_0^{t_c} f(C, S > 1, t, M) dt$	[1/h]

Table 2  
Failure probabilities at the end of operating time duration (time dependence is  $t^\alpha$ )

Cause type $C$	Failure mode type $M$	Failure probability	Dimension of function $g$
1	0	$1.0 - \exp[-g(C, S = 1, M)t_s^\alpha - g(C, S > 1, M)(t_c - t_o)^\alpha]$	$[1/h^{\alpha+1}]$
1	1	$1.0 - \exp\left[-\frac{g(C, S = 1, M)}{\alpha+1}((t_o + t_s)^{\alpha+1} - t_s^{\alpha+1}) - \frac{g(C, S > 1, M)}{\alpha+1}(t_c^{\alpha+1} - (t_c - t_o)^{\alpha+1})\right]$	$[1/h^{\alpha+1}]$
1	2	$1.0 - \exp\left[-\frac{g(C, S = 1, M)}{\alpha+1}(t_o + t_s)^{\alpha+1} - \frac{g(C, S > 1, M)}{\alpha+1}t_c^{\alpha+1}\right]$	$[1/h^{\alpha+1}]$

summed to be as follows:

$$f(C = 1, S, t, M) = g(C = 1, S, M)t^\alpha, \quad (20)$$

where the function  $g(C = 1, S, M)$  is the time independent part of function  $f$ . In this case, the failure probabilities for  $C = 1$  become as shown in table 2.

There are many different causes for one failure mode. If more than one causes affect on a component, the failure rate has to be determined by considering all these causes. But the dimension of the function  $f$  is [-] or [1/h] depending on the combination of cause and failure mode. Then it is impossible to define the total failure rate merely by the summation of failure rates produced by each cause. Therefore the compound effect of many causes have to be considered in the failure probability.

The total failure probability depends on a specific combination of causes. In some cases, the total failure probability may be greater than the summation of the failure probabilities produced by each cause. For example, if there are stress and corrosion, the resultant failure probability may be fairly greater than the summation of the two failure probabilities produced by each cause. The phenomenon of stress corrosion cracking is this kind of failure.

In another extreme case, the total failure probability is almost the same as the maximum one among the failure probabilities produced by each cause alone.

In the present model, the total failure probability with more than one causes is assumed to be the Boolean summation of the failure probabilities produced by the individual causes. This is expressed in the following equation:

$$\text{Total failure probability} = \sum_j (\text{failure probability})_{C_j}, \quad (21)$$

where  $(\text{failure probability})_{C_j}$  means the failure probability produced by cause  $C_j$ .

## 7. Comparisons with failure data

In most reliability analyses, the failure rate is treated as a constant value, so there are only few data that show the time dependent failure rate. The causes for a failure are not explicitly considered. That's why the comparisons were performed for the time dependence, and not for the dependence on a cause.

The present model assumed that the failure rate is proportional to  $t^\alpha$  for the continuous type cause as

shown in section 6:

$$\text{Failure rate} = g t^\alpha. \quad (22)$$

Here we consider the case in which there is only one cause for a failure, and in which the operating and cause acting time durations are equal to each other. Then the cumulative failure probability becomes:

$$\text{Cumulative failure probability} = 1.0 - \exp\left(-\frac{g}{\alpha+1}t^{\alpha+1}\right), \quad (23)$$

where  $t$  is the time after the initiation of operation. From eq. (23), the failure probability distribution  $\varphi(t)dt$  is obtained as follows:

$$\varphi(t)dt = g t^\alpha \exp\left(-\frac{g}{\alpha+1}t^{\alpha+1}\right)dt. \quad (24)$$

This is the Weibull distribution.

The comparisons between failure data and model were performed by use of eq. (22) or (23), and the values of  $\alpha$  were determined from actual failure data.

Boesebeck and Homke [8] have shown the time dependent failure rates of main steam fittings for three different diameters, which are shown in fig. 2. From fig. 2 and eq. (22), the values of  $\alpha$  are obtained to be 1.66 and 7.64 for the diameter greater and less than 8 inches, respectively.

Behmann [9] has shown the time dependent failure

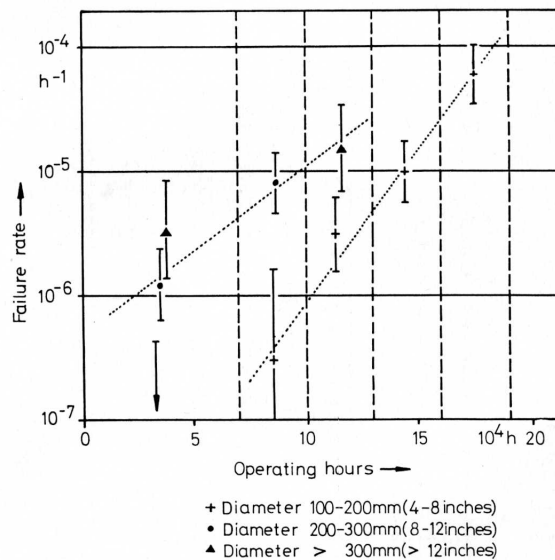


Fig. 2. Time dependent failure rates for inspected main steam fittings for different diameters (by Boesebeck & Homke).

Table 3  
Values of  $\alpha$  (estimated from failure data)

Experimenter	Component	Data type	$\alpha$
Boesebeck & Homke	Main steam fitting Diameter > 8 in	Failure rate	1.66
	Diameter < 8 in	Failure rate	7.64
Behmann	Travelling wave tube	Failure rate	2.0
		Failure rate	1.86
		Failure rate	2.82
Kieron	TTL devices	Cumulative failure probability	0.01
Kobayashi	Solder & Solder Joint	Cumulative failure probability	0.86
Lambert	Solder	Cumulative failure probability	-0.06

rates for three different type travelling wave tubes. Kieron [10] has shown the cumulative failure probability for TTL devices. His data were compared with eq. (23). Kobayashi [11] has shown the cumulative failure probability versus thermal cycling test for solder or solder joints. Lambert [12] has also shown the cumulative failure probability versus thermal cycling for solder. If the number of thermal cycles is proportional to the operating time  $t_o$ , the values of  $\alpha$  are also obtained from the last two data. From above data, the values of  $\alpha$  were obtained as shown in table 3.

These results show that  $\alpha$  varies very widely; from 0 to 8. In some cases, the failure rate is time independent, that is,  $\alpha = 0$ . In other cases, strong time dependence is shown. This fact indicates that the time dependence of the failure rate depends on component kind, failure mode and cause. Therefore,  $\alpha$  is determined for individual cases from the actual data.

The time dependence of the failure rate was well expressed by eq. (22) and this equation can produce the simple expressions for the cumulative failure probability and failure probability distribution as shown in eqs. (23) and (24).

## 8. Discussion and conclusions

The present model has been constructed in order to treat the effect of extreme environmental conditions on the system reliability. The failure rate is assumed to be a function of cause, of severity of cause, of cause acting duration and of failure mode, as explained in this paper.

The expressions for the failure probabilities were obtained from this failure model on some assumptions. For the practical applications, the stand-by time duration is not a fixed value and the averaging procedure is required with respect to this time duration. Further there is the case in which the cause acts on the component for a certain time duration during stand-by time, and not continuously till the end of the operation. In these cases, the failure probabilities are different from the results shown in table 1 or 2. But those failure probabilities are obtained in the similar way as shown in this paper.

The effect of extreme environmental conditions is easily treated by using this failure model. It is also possible to treat the common mode failure, because the common mode failure is produced by some causes, and the conditional failure probabilities under various conditions can be obtained from this model.

Human factors are treated as causes for a failure mode. The failure rate has a time dependence, then an aging effect of components can be included in the result of the reliability analysis.

The secondary failure will be treated by using this failure model. But it requires further study on the treatment of the relation between component failures and their effects on an environmental condition.

The authors are now developing a computer program which can treat these problems. The most important feature for the actual application of this model is to collect detailed data of time dependent and conditional failure rates under various extreme conditions.

In this model, one hundred values of the function  $f$

are required for only one failure mode, that is, 20 causes  $\times$  5 steps of severity. Further, the additional 45 values of the failure rate  $\lambda_i$  are required in the case of  $C = 0$  and  $M = 1$  or 2, that is 9 impact type causes  $\times$  5 steps of severity. But, not all the causes influence a specific failure mode, and the failure is determined by a few main causes. Therefore, there are not so many data for one failure mode necessary. Moreover, the data for the causes: calibration, installation, maintenance, operation or operator, test procedure, and manufacturer, can be commonly used for many failure modes.

At the present time these kinds of data are not obtained. For a reliability analysis the collection of these data is important and has to be performed in consideration of this kind of analytical method.

This paper presented a new failure model which can treat the effect of an extreme environmental condition and the common mode failure.

Causes were classified into two types: impact and continuous types, and failure modes were into three types: demand, operating, and stand-by type failure modes. The expressions of failure probabilities were obtained in relatively simple form for all the combinations of cause and failure mode types.

This failure model was compared with the data of time dependent failure rates. The time dependence was well expressed by the  $\alpha$ th power of time. The values of  $\alpha$  were in very wide ranges from 0 to 8, then  $\alpha$  should be determined from actual data for individual causes and failure modes.

#### Nomenclature

$C$	cause for a failure
$F$	failure rate
$f$	a function of $C, S, t, M$
$g$	time independent part of the function $f$
$M$	failure mode
$N(t)$	number of normal components
$S$	severity of a cause
$t$	time
$t_o$	operating time duration
$t_s$	stand-by time duration
$t_c$	cause acting duration
$\alpha$	exponent of $t$

$\lambda_i$  failure rate which expresses a latent damage  
 $\varphi(t)$  failure probability distribution

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