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Quantitative Evaluation of Surveillance Test Intervals Including Test-Caused Risks

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ABSTRACT

Concerns have been raised regarding the adverse safety impact of surveillance testing and generally overburdensome surveillance requirements. To evaluate these concerns, the risk-effectiveness of surveillance tests has been studied with explicit consideration of the adverse risk impact, in conjunction with the beneficial risk impact. This report defines the adverse effects of surveillance testing from a risk perspective, and then presents the methodology by which the adverse risk impact can be quantified, focusing on two important kinds of adverse risk impact of surveillance testing: (1) risk impact of test-caused trips and (2) risk impact of test-caused equipment wear.

Using the methodology presented, these risk impacts are evaluated for a selected set of surveillance tests for demonstration examples. The results of the risk-effectiveness evaluation are provided along with the insights from the sensitivity analyses.

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EXECUTIVE SUMMARY

Surveillance testing is required by Technical Specifications to assure that the standby systems important to safety will start and perform their intended functions in the event of plant abnormality. However, the surveillance tests may have adverse impact on safety, because of their undesirable side effects such as initiation of plant transients during testing or wearing-out of safety systems due to testing, as evidenced by the operating experience of the plants.

The objective of this report is three-fold: (1) to define the concerns, i.e., the potential adverse effects of surveillance testing, from a risk perspective, (2) to present a methodology to evaluate the risk impact of those adverse effects of testing, (3) to demonstrate the methodology to quantitatively evaluate surveillance requirements by applying it to specific tests. The focus is placed on two important kinds of "test-caused" risk impact associated with the adverse effects, i.e., the risk impact of plant transients which may occur during testing and the risk impact of equipment wearing-out which is caused by testing.

The risk impact of test-caused plant transients can be evaluated by recognizing that the transients, which cause or require a reactor scram, are initiating events as typically called in probabilistic risk assessments (PRAs). The risk impacts of all types of initiating events are assessed in PRAs which model the functions of the various safety systems and the operator actions following the initiators. Therefore, we assessed the risk impact of test-caused transients through the risk impacts of initiating events in the PRA model.

The risk impact of test-caused equipment degradations can be assessed using the test-caused component degradation model which was developed in this study from the considerations of the stresses on equipment and the test-caused and aging degradation mechanisms. Using the model in the framework of a PRA, we evaluated the core-damage frequency impact of progressive wearing-out of the equipment due to periodic testing.

The methods for evaluating the adverse effects of testing were applied to several surveillance tests conducted at boiling water reactors, such as the tests of main steam isolation valves, turbine overspeed protection system, and emergency diesel generators. The risk associated with these tests was assessed using a PRA conducted in support of the NUREG-1150 study. Risk-effectiveness evaluations were performed by comparing the risk impact of test-caused plant transients and equipment degradations to the risk impact of the beneficial effect of testing that results from the detection of failures. Sensitivity analyses were also carried out on the risk impact versus test interval. The results of and insights from these analyses are useful in redefining the standard test intervals from a safety or risk perspective.

In summary, the safety significance or risk-effectiveness of surveillance test requirements can be evaluated with explicit consideration of the adverse effects of testing, in addition to the beneficial effect. The quantitative risk-evaluation results can be used in the decision making process for the establishment of the safety significance of the surveillance testing and for the screening of the surveillance requirements. These results should be used in conjunction with the qualitative evaluation results from engineering considerations and operating experience, such as consideration of radiation exposure to plant personnel or unnecessary operator burden of work resulting from the test requirements.

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1. INTRODUCTION

1.1 Background and Objective

In nuclear power plants, surveillance tests are required to detect failures in standby equipments as a means of assuring their availability in case of an accident. However, the surveillance tests may have adverse impact on safety, because of their potential adverse effects such as occurrence of plant trips or excessive wear of equipment due to testing, as evidenced by the operating experience of the plants.[1] This potential for adverse impact on safety becomes aggravated due to the volume and frequency of the present surveillance requirements that are often characterized as too much-too often.[2,3]

To address the concerns with surveillance testing, i.e., adverse impact on safety and overburdensome surveillance requirements, it is necessary to evaluate the safety significance or risk-effectiveness of the surveillance requirements with consideration of the adverse effects of testing. Although qualitative engineering judgment still will play a significant role in any changes of technical specifications or in the evaluation of the surveillance requirements, the reliability and risk analysis of the requirements, where possible, also can provide an important safety perspective.

This report presents a methodology that can be used to evaluate the risk impacts associated with surveillance tests and thereby to help establish the safety significance of technical specifications surveillance requirements. Since the method for evaluating the beneficial risk impact of testing, i.e., the risk reduction due to a test, has been developed,[4] this report focuses on the method for evaluating the adverse risk impact associated with surveillance testing, i.e., the risk increase due to or as a result of testing. The quantitative methodology is applied as a demonstration to several surveillance tests conducted at boiling water reactors, such as the tests of main steam isolation valves, turbine overspeed protection system, and emergency diesel generators.

1.2 Scope

Several kinds of adverse effects, and thereby adverse risk impacts, are associated with surveillance testing, as defined in Section 3. We present risk-based methodologies with demonstrative applications in this report, focusing on two important kinds of adverse risk impacts of surveillance testing: (1) risk impact of test-caused trips, and (2) risk impact of test-caused equipment wear.

The risk analysis of surveillance tests based on these methodologies will provide a quantitative basis from a safety perspective, for evaluating surveillance tests that generate significant safety concerns due to: (1) potential trips which challenge safety systems; and (2) significant equipment wear-out which increases the unavailability of safety systems or functions, and thereby reduces the plant's capability for mitigating accidents.

1.3 Organization of the Report

Section 2 of this report presents the basic concepts for evaluating the risk-effectiveness of surveillance tests. Section 3 defines, in more detail, the risk impacts associated with tests, focusing on the enumeration of the adverse effects of tests.

Section 4 briefly presents the formulas for evaluating test-detected risk contribution. Section 5 provides a methodology, based on probabilistic risk assessment (PRA), for evaluating the risk impact associated with test-caused transients with examples of applications. Section 6 presents component degradation models for analyzing the risk associated with progressive component degradations due to surveillance testing. Section 7 addresses summary and conclusions. Appendix A describes the test-caused transient events identified from the data analysis of this study, and Appendix B derives formulas for maximum test-caused degradation and aging parameters, which are needed to evaluate the risk impact from test-caused equipment wear.

2. BASIC CONCEPTS

Consider a surveillance test which is conducted on some component or system. To determine the risk-effectiveness of the test, we need to define the risk contribution, which is caused by the test, and the risk contribution, which is detected by the test. Let

$$R_D = \text{the risk contribution which is detected by the test} \tag{2.1}$$

and

$$R_C = \text{the risk contribution which is caused by the test.} \tag{2.2}$$

The risk contributions, R_D and R_C, can be any risk measures, such as the unavailability contributions associated with the test, or the core damage frequency contributions associated with the test. Alternatively, the risk contributions of public health associated with the test can be the focus. However, we shall generally focus on core damage frequency contributions.

The risk contribution detected by the test is the contribution associated with failures that occur between tests and are detected by the test. The risk contribution caused by the test is associated with failures or degradations which are caused by the test or are related to the performance of the tests, such as plant trips. This risk contribution is the adverse effect of the test.

One advantage of separating risk contributions detected by the test from those caused by the test is that it allows the test to be evaluated for the risk-effectiveness. The test is risk-effective if the risk detected by the test is greater than the risk caused by the test:

$$R_D > R_C : \text{ risk-effective test} \tag{2.3}$$

Conversely, the test is risk-ineffective if the test-caused risk contribution is greater than the test-detected risk contribution:

$$R_C > R_D : \text{ risk-ineffective test} \tag{2.4}$$

The total risk, R_T, which is associated with the test, is simply the sum of R_D and R_C:

$$R_T = R_D + R_C \tag{2.5}$$

R_T is the contribution standardly computed in PRAs. Often R_C is assumed to be zero. However, in many cases, R_C can be significant as evident from the operating experience of the plants.

Another advantage of separating R_D from R_C is that sensitivity studies and parametric studies can be carried out to determine test conditions or regimes in which the test is effective or ineffective. In this way, requirements on test conditions can be determined, regions for human error impacts can be identified, performance criteria can be established, and conditions under which the test needs to be improved can be determined.

Figure 2.1 shows a conceptual plot of the risk detected by the test, R_D, and the risk caused by the test, R_C, versus a test parameter of interest. The figure shows only one possible pattern of behaviors in R_D and R_C; other patterns also can easily be envisioned. The test parameter can be the test interval, the probability of a trip occurring during the test, the aging caused by the test, or any other relevant test parameter. With studies such as that conceptualized in the figure, regimes and conditions for risk-effective tests can be identified. Present tests can be evaluated with regard to these regimes, and criteria which ensure that the test is risk-effective can be determined. These evaluations also can provide a basis for prioritizing the tests with regard to test-caused contributions and sensitivities.

A beneficial, calculational feature of determining the risk-effectiveness of a test is that only relative evaluations are involved. To see these more clearly, the criterion for a risk-effectiveness test, Equation (2.3), can be re-expressed as follows:

$$\frac{R_D}{R_C} > 1 : \qquad \text{risk-effective test} \tag{2.6}$$

Similarly, the criterion for a risk-ineffective test, Equation (2-4), can be re-expressed as:

$$\frac{R_D}{R_C} < 1 . \qquad \text{risk-ineffective test} \tag{2.7}$$

Thus, the ratio of the risk contributions, R_D and R_C, is the factor determining the risk-effectiveness of the test.

The ratio R_D/R_C can be termed the risk-effectiveness parameter, α, of the test:

$$\alpha = \frac{R_D}{R_C} \tag{2.8}$$

The risk-effectiveness or risk-ineffectiveness of the test is denoted by a risk parameter, α, greater than or less than 1. A risk-effectiveness parameter α equal to 1 can be termed a risk-neutral test:

$$\alpha > 1 : \ \text{risk-effective test} \tag{2.9}$$

$$\alpha < 1 : \ \text{risk-ineffective test} \tag{2.10}$$

$$\alpha = 1 : \ \text{risk-neutral test} \tag{2.11}$$

In addition to the relative evaluation of the risk-effectiveness, the total risk contribution, R_T, can be evaluated for its effectiveness with regard to a given criterion. The criterion for R_T can be an absolute criterion, or can be expressed as a relative fraction of the overall risk considering all risk contributors. The evaluation of the total test risk provides an additional option or means for determining acceptable test conditions and characteristics.

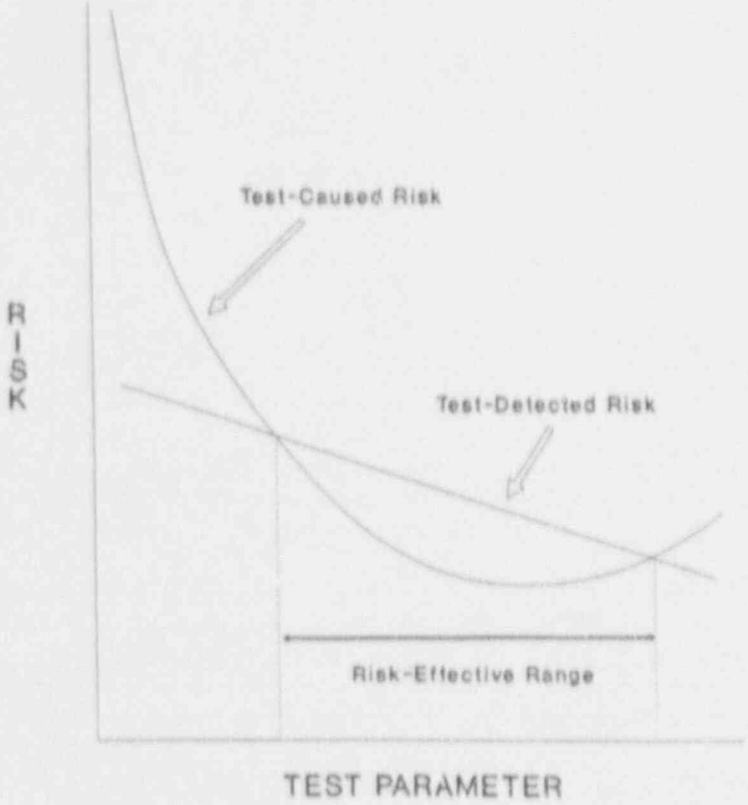


Figure 2.1 Conceptual plot of test risk contributions versus test parameter for determining risk-effective test characteristics.

3. DEFINITIONS OF TEST-DETECTED RISK AND TEST-CAUSED RISK

This section discusses, in more detail, the definitions for the risk contribution, R_D, detected by the test and the risk contribution, R_C, caused by the test. These discussions also will show the specific contributions that are associated with these two major categories of risk contributions. The subsequent sections develop formulas for the test-detected risk contribution and for the test-caused risk contribution.

As were discussed in the previous section, R_D is the contribution associated with detecting a failure which has occurred between tests:

R_D = the risk contribution associated with the tested component failing between tests and being detected at a test. (3.1)

When the component fails, it can fail in a number of failure modes, e.g., fails open, fails closed, or fails to actuate. The above definition of R_D can apply to a specific failure mode or to several failure modes, if the test is capable of detecting several failure modes. The failure modes of principal interest are those which are identified in the PRA.

If the test is performed on a system instead of a component, then the above definition still applies when the tested component is interpreted as the tested system. If the test is performed on multiple components and is able to detect failure of any component, then the above definition applies with the tested component interpreted as any of the components tested.

The failure of the tested component, which occurs between tests, is associated with time-related failures of the component. When the component failure rate is divided into a time-related contribution and a cycle-related (demand-related) contribution, then R_D is associated with the time-related failure rate. As we will discuss in Section 6, the test-caused risk contribution, R_C, is associated with both time-related and cycle-related contributions. The time-related failures of the component included in R_D includes failures from all time-related causes, hardware and human.

R_D can also be applied to a group of tests as well as an individual test. When applying R_D to a group of tests, the interest is in evaluating the risk-effectiveness of a test program or test procedure. The risk contributions would then include not only the sum of the individual test contributions, but also any interactions among the tests.

Turning now to the test-caused risk contribution, R_C, as explained in the previous section, R_C is the risk contribution which is caused by the test itself and is associated with the test. Table 3.1 lists the different risk contributions, which can be associated with a test, along with their root causes. These are not all the possible contributions, but are those that are most likely to be encountered.

All these risk contributions may not be associated with a given test. The test will have to be evaluated to determine which of the contributions are significant. As part of the evaluations, sensitivity studies also can be performed to prioritize the test-caused risk contributions for given test characteristics or human error rates. Enhanced controls can be placed on the test to provide protection against these sensitivities to given characteristics or errors. Controls may be loosened for tests which are not sensitive or which are not important.

Table 3.1 Test-Caused Risk Contributions and Their Root Causes

Identifier	Risk Contribution	Root Cause of the Risk
R_{trip}	Risk from test-caused trips	Human error, equipment failure, procedure inadequacy.
R_{wear}	Risk from test-caused equipment wear	Inherent characteristics of the test, procedure inadequacy, human error.
R_{state}	Risk from test misconfigurations or component restoration error	Human error, procedure inadequacy.
R_{down}	Risk associated with test downtime in carrying out the test	Unavailability of the component during the test. Affected by the test override capability.

The test-caused risk contributions listed in Table 3.1 are all subject to a risk analysis based on the risk measure, core damage frequency, or other risk measures of higher levels, such as releases of radioactive material, offsite consequences of the radioactive material , or public health risk. Although other risk measures at a lower level, such as safety system unavailability, can be used to evaluate R_{wear}, R_{state}, and R_{down}, the test-caused risk contribution due to transients, i.e., R_{trip}, cannot be evaluated using the safety system unavailability as the risk measure, because the unavailability will not be affected, in general, by the variation in the probability of a trip occurring during a test. The use of a same risk measure, where possible, in analyzing all the different kinds of risk contributions associated with a test will facilitate the evaluation of risk-effectiveness of the test. Hence, the core damage frequency is used in this report as the primary risk measure to quantify the various risk contributions associated with tests.

Besides those defined in Table 3.1, there are two other adverse effects of a test that may be encountered sometimes: radiation exposure to plant personnel and unnecessary burden on plant personnel. These two adverse effects are different from those delineated in Table 3.1 in that: (1) the radiation exposure to plant personnel is not amenable to a risk analysis based on the core damage frequency as a risk measure, because the core damage frequency, or some other lower-level risk measures, will not be affected by the amount of the radiation exposure to plant personnel; and (2) the unnecessary burden on plant personnel in general also is not subject to a risk analysis. However, these adverse effects, although excluded from the quantitative risk analysis, can be considered qualitatively along with the results of quantitative risk analysis for the evaluation of surveillance requirements.

From Table 3.1, the risk contribution caused by a test, R_C, can be expressed in a general form as:

$$R_C = R_{trip} + R_{wear} + R_{state} + R_{down} \tag{3.2}$$

where for any specific test, a number of the contributions on the right-hand side will not be relevant, or will not be significant. When a test program or test procedure is evaluated for its risk-effectiveness by conducting tests on a number of individual components, then the test-caused contributions for each test plus the contributions from any test interactions will need to be considered.

Among the various root causes of the risk delineated in Table 3.1, human errors are the root cause which previous studies[5,6] concentrated on to address adverse effects of testing. In terms of the risk contributions in the table, the studies mainly focused on R_{state} that is most likely to be caused by human errors, with some consideration of R_{down}.

Table 3.1 shows that human errors also may cause two other kinds of risk contributions, i.e., R_{trip} and R_{wear}, in addition to R_{state}. Human errors are generally classified as errors of omission and errors of commission. If the operator forgets to return a manually operated valve to its normal condition after a test, then an error of omission occurs. If the operator uses an incorrect set level when calibrating a bistable amplifier, then an error of commission occurs. Note also that where redundant components (or systems) are tested, there is always potential for a common cause failure. For instance, if two normally-open isolation valves were closed for testing, and the operator forgets to open both following the test, then a common cause failure will occur due to errors of omission.

The risk also can be evaluated with respect to a given specific root cause, such as human errors (or more specifically, errors of omission or commission). For instance, presume that human errors during a given test may cause a transient to occur and also may cause the components not to be restored to the normal status. The risk contribution due to potential human errors during the test can then be estimated by first evaluating the contributions of the risk from test-caused trips, R_{trip}, and from component restoration error, R_{state}, due to only human errors, and then adding the contributions.

In evaluating the risk-effectiveness of a test (or group of tests), the test-detected contribution, R_D, can either be compared to specific test-caused contributions or to all relevant test-caused contributions constituting R_C. If only specific test-caused contributions are considered, then the evaluation of the risk-effectiveness of the test is considered with regard to the specific test-caused contributors. For example, if test-caused risk contributions due to trips, R_{trip}, are only considered and we assess that $R_D > R_{trip}$, then we can say that the test is risk-effective with regard to test-caused trips. When more test-caused contributions are considered, then broader conclusions can be reached.

4. FORMULAS FOR THE TEST-DETECTED RISK CONTRIBUTION

The formula for the risk contribution, R_D, which is detected by the test, can be determined by considering the risk reduction, which results when a failure is detected by the test. We shall consider a test performed during operation and shall assume no significant inefficiencies in test detection of failures, though that can be added later. Assume that when the test is performed on the component or system, it detects the component (or system) to be in a down state. The component was down because it suffered a failure since the previous test. Upon discovery of the failure, the component is subsequently restored to an up state after some repair time.

When the component is down, the core damage frequency (or other risk measure of interest) is R_1:

R_1 = the core damage frequency with the component down (4.1)

The "down risk", R_1, is calculated using standard reliability techniques or PRA techniques, with the assumption that the component is in a down state. The subscript "1" in R_1 denotes an unavailability of one associated with the component being down. Any component reconfigurations and required additional testing are incorporated in the calculation of R_1.

Immediately after the test, when the component has been restored to an up state, the core damage frequency is R_0:

R_0 = the core damage frequency with the component up (4.2)

The "up risk", R_0, is the core damage frequency or other risk measure calculated using standard techniques, but with the assumption that the component is in an up state. The subscript "0" denotes an availability of zero associated with the component being up.

The reduction of core damage frequency, ΔR, associated with the conduction of a test, when a failure has been detected, is consequently $R_1 - R_0$:

$$\Delta R = R_1 - R_0 \tag{4.3}$$

To obtain the expected reduction of core damage frequency associated with the test, we must consider the probability of the test actually detecting a down state of the component.

Assume that the component failure rate is λ. The failure rate, λ, includes component failures occurring between tests, and also includes human errors which inadvertently place the component in a down state between tests. If λ is assumed to be constant, then the probability, p, that the component is found to be in a down state, when a test is conducted, is:

$$p = 1 - \exp(-\lambda T) \tag{4.4}$$

or

$$p \cong \lambda T, \tag{4.5}$$

where T is the surveillance test interval and where the last expression is a valid first-order approximation for $\lambda T < 0.1$. As was discussed, λ is the time-related failure rate for failure causes occurring between tests.

Thus, the expected reduction of core damage frequency, $\Delta\bar{R}$, for the test is:

$$\Delta\bar{R} = p\,(R_1 - R_0) \qquad (4.6)$$

or to first order,

$$\Delta\bar{R} \cong \lambda T\,(R_1 - R_0). \qquad (4.7)$$

The expected reduction of core damage frequency could be associated with the risk contribution detected by the test. However, we shall include the duration of the risk contribution as part of the definition of the risk contribution detected by the test. This definition will allow for broader applications.

For a constant failure rate, the time of failure is uniformly distributed between the tests, when a failure occurs. Thus, the average time the component will be down, when it does go down, is T/2. Consequently, the risk contribution detected by the test, R_D, which includes the duration of the downtime is defined as:

$$R_D = \Delta\bar{R}\;T/2 \qquad (4.8)$$

$$= p\,(R_1 - R_0)\,T/2 \qquad (4.9)$$

or to first order,

$$R_D \cong \frac{1}{2}\lambda T^2\,(R_1 - R_0). \qquad (4.10)$$

Thus, we have arrived at the final formula for R_D. If we are focusing on the core damage frequency, then R_D as defined by Equations (4.8) - (4.10) is the average core damage probability contribution detected by a test because of the multiplication by the time duration T/2. We can obtain an average core damage frequency contribution detected by a test by dividing by the test interval T. If we let $\bar{R}_D$ denote the average core damage frequency contribution detected by a test then:

$$\bar{R}_D = \frac{R_D}{T} \qquad (4.11)$$

$$\cong \frac{1}{2}\lambda T\,(R_1 - R_0) \qquad (4.12)$$

$\bar{R}_D$ is the core damage frequency contribution associated with a test, which is standardly calculated in PRAs. Either definition of the risk contribution detected by the test, R_D or $\bar{R}_D$, will yield the same results as long as consistently used. Using Equations (4.10) and (4.12), the core damage probability or core damage frequency contribution detected by a test is straightforwardly computed using standard PRA models.

5. RISK IMPACT OF TRANSIENTS CAUSED DUE TO TESTING

One of the safety concerns with surveillance testing at power is that a transient may be initiated during the testing. The impact of test-caused transients on the plant is first described from a risk perspective, and then the formulas for evaluating the risk impact of these transients are developed within the framework of a plant's PRA model. The formulas will then be applied to a selected set of tests that may cause a transient.

5.1 The Impact of Test-Caused Transients on the Plant from a Risk Perspective

A nuclear power plant may experience a transient that may cause or require a reactor trip, due to a performance of testing while the plant is at power. Once the test-caused transient occurs, it generally deteriorates the process condition of the plant. The risk impact of the test-caused transient or the resultant trip depends on the performance of the plant's safety systems and sometimes on the operator actions following the transient.

As an example, the main steam isolation valves (MSIVs) of pressurized water reactors (PWRs) are periodically partial-stroke tested (typically 10% closed) during power operation. However, the partial-stroke test of an MSIV may result in a full closure of the valve due to an operator error in performing the test or to a failure of the test equipment. The inadvertent full closure of the MSIV during testing reduces the heat removal capability of the power conversion system, and thus may require intervention of the neutron chain reaction through the reactor protection system (RPS), or the operators, if the RPS fails to properly respond. Even after the successful intervention of the heat production in the reactor, successful performance of some safety systems other than the RPS also will be required to prevent potential core damage.

To evaluate the risk contribution of test-caused transients to the total plant risk, we, therefore, should consider the various responses of the safety systems and operators following the transient. These considerations are typically done in PRAs, in which the various responses of the safety systems and the operators relevant to the risk assessment of the plant are taken into account, using event trees for delineating progressions of accident sequences, and system fault trees for identifying the failure modes and their effects on the system unavailability. Therefore, the risk contribution from test-caused transients to the plant risk can be evaluated within the framework of a PRA model. The following section presents PRA-based formulas for evaluating the risk impact of test-caused transients.

5.2 PRA-Based Formulas for the Risk Impact of Test-Caused Transients

One of the most critical elements in a PRA is initiating events that may occur during the plant operation. The initiating events are the events that cause or require a reactor scram. Because the transients that are induced by testing will cause or require a reactor scram, they also can be considered as initiating events from a viewpoint of PRA.

The risk impact of test-caused transients can be estimated in a similar manner as the risk impact of initiating events is assessed in PRAs. Given a PRA model on the plant, the risk impact of test-caused transients can be evaluated through the initiating events of the model, because the initiating events of the PRA include test-caused transients as well as those transients caused due to reasons other than tests, such as a transient induced by a random hardware failure in the main feedwater system.

To illustrate how a PRA model can be used to estimate the risk contribution from test-caused transients, R_{trip}, assume that the test-caused transient belongs to a specific initiating event group, say the j-th initiating event group (denoted as IE-j). Also, assume that among all the sequences modeled by the PRA, the accident sequences beginning with the j-th initiating event group can be represented as:

$$\begin{aligned} C_1 &= I_j\, B_{11}\, B_{21}\, B_{31}\ \cdots \\ C_2 &= I_j\, B_{12}\, B_{22}\, B_{32}\ \cdots \\ &\cdots \\ C_N &= I_j\, B_{1N}\, B_{2N}\, B_{3N}\ \cdots \end{aligned} \tag{5.1}$$

where

C_i = frequency of the i-th accident sequence cut set,
I_j = frequency of the j-th initiating event group, and
B_k = unavailability of the k-th basic event.

The basic events in the above sequences indicate all the possible ways of plant or operator responses leading to core damage, following the initiating events that belong to the j-th initiating event group. The basic events may be events related to safety system hardware, human error, or accident recovery. Since the test-caused transient belongs to the j-th initiating event group, the core damage of the plant will occur following one of the accident sequences in Equation (5.1), if it happens as a result of the test-caused transient.

If we let

$$R_{IE\text{-}j} = \text{the risk contribution of the j-th initiating event group to the total plant risk,} \tag{5.2}$$

then $R_{IE\text{-}j}$ is the sum of the frequencies of all the accident sequence cut sets that begin with the j-th initiating event group:

$$R_{IE\text{-}j} = \sum_i C_i \tag{5.3}$$

Note that the sum of the risk contributions from all the initiating event groups is the total plant risk or core damage frequency R_T:

$$R_T = \sum_i R_{IE\text{-}i} \tag{5.4}$$

where the sum is over all the initiating event groups modeled in the PRA.

The test-caused risk contribution from transients then is a subset of the risk contribution due to the j-th initiating event group which incorporates the test-caused transients; i.e.,

$$R_{trip} \leq R_{IE\text{-}j} \tag{5.5}$$

Therefore, we obtain the following equation:

$$R_{trip} = \phi\, R_{IE\text{-}j} \tag{5.6}$$

In Equation (5.6), ϕ is the proportion by which the initiating event group is caused by the test-caused transients; in other words, it is the proportion by which the frequency of the initiating event group is attributable to the test-caused transients.

The value of the proportion, ϕ, will be 1 if the frequency of the initiating event group is only due to the test-caused transients. On the other hand, the value of ϕ will be 1/2, if only a half of the frequency of the initiating event group is attributable to the test-caused transients. In general, the value of ϕ lies between 0 and 1:

$$0 < \phi \leq 1 \tag{5.7}$$

Where the test-caused transients are associated with several different initiating event groups, the test-caused risk contribution from transients can be obtained by calculating R_{trip} using Equation (5.6) for each of the associated initiating event groups, and then adding them up.

The proportion ϕ for the relevant initiating event group is the contribution of the initiating events caused by the test to the initiating event group in terms of the probability of occurrence. Hence, it can be estimated by analyzing the plant operating data as follows:

$$\phi = \frac{N_{test}}{N_{IE\text{-}j}} \tag{5.8}$$

where

N_{test} = the number of transient events due to the test, and
$N_{IE\text{-}j}$ = the number of transient events belonging to the relevant initiating event group.

Substituting Equation (5.8) into Equation (5.6) we have:

$$R_{trip} = \frac{N_{test}}{N_{IE\text{-}j}} R_{IE\text{-}j} \tag{5.9}$$

where $R_{IE\text{-}j}$, i.e., the risk contribution of the initiating event group to the total plant risk, can be easily obtained from a PRA model.

5.3 Evaluation of the Risk Impact of Test-Caused Transients

5.3.1 Categories of Transients

To evaluate the risk impact associated with test-caused transients through the risk contributions of initiating event groups, it is necessary to identify which initiating event group the test-caused transient event belongs to. However, the degrees of detail of the test-caused transients and the initiating event groups are usually different from each other, because the various types of transients or initiating events are combined into a small number of initiating event groups in a PRA. Therefore, to associate the test-caused transients with the initiating event groups, we can preferably use transient categories that are more detailed than the initiating event groups of the PRA.

The transient categories that may be used to estimate the risk contribution from test-caused transients are those which are actually used to derive the initiating event frequencies in PRAs. These categories were originally developed to analyze the historical transient events in the anticipated transients without scram (ATWS) study.[7] The ATWS study by the Electric Power Research Institute (EPRI) defined 37 Boiling Water Reactor (BWR) and 41 Pressurized Water Reactor (PWR) categories based on the consideration of different characteristics of a variety of transient events that can occur in the plants.

Although the follow-up study,[8] conducted by Idaho National Engineering Laboratory (INEL) for analyzing the frequencies of transient initiating events to be used in PRAs, suggested some changes in the categorization of transient events, the categories suggested by INEL are similar to the EPRI categories. Furthermore, the expansion and update of the EPRI data base was done on the basis of the EPRI categories. Thus, the original EPRI transient categories can be used to estimate the risk impact of test-caused transients.

5.3.2 Procedure for the Risk Impact Evaluation with Example Applications

This subsection shows how the risk impact of test-caused transients can be evaluated using the transient categories based on the formulas developed in Section 5.2. Example evaluations of the risk impact also are provided for the following four different kinds of tests at BWRs:

(a) Test of the main steam isolation valve (MSIV) operability,
(b) Test of the turbine overspeed protection system (TOPS),
(c) Control rod movement test, and
(d) Slave relay test for the engineered safety features actuation system (ESFAS).

Table 5.1 shows the various attributes of the tests including the purpose, the surveillance test period and the way the test is conducted, the characteristics, and the adverse effects of the tests. The test periods are typical ones; there may be a slight variation depending on the specific plants. These attributes can be used for qualitative evaluations of the tests. As previously discussed, the final decision on the safety significance or risk-effectiveness of surveillance test requirements can be made based on the qualitative evaluations, in conjunction with the quantitative results of the risk analysis, following the method we present in the report.

The following describes the procedure for evaluating the test-caused risk contribution from test-caused transients, R_{trip}, with examples of applications.

(1) Identify the transient categories associated with the transient that may be caused during or as a result of the test

To evaluate the risk contribution due to test-caused transients based on transient categories, first it is necessary to identify the transient categories which are associated with the transient that may be caused during or as a result of the test. The transient categories associated with the test-caused transient can be identified from the EPRI transient categories, by considering how the test is conducted and what kinds of transients the test can cause, or has caused in the operating history of the plant.

Table 5.1 Surveillance Tests that may Cause Transients[1]

Test	Purpose	Period and Conduction	Characteristics	Adverse Effect	Comments
MSIV Operability Test	Prevent the discharge of primary coolant outside the containment.	Quarterly. Verify full closure within a specified time interval (typically between 3 and 5 seconds).	MSIVs also send a signal to the reactor protection system to trip the reactor upon 10% closure.	Caused reactor trips.	Significant problems were discovered during testing of MSIVs; e.g., failed relays and limit switches and contamination of air supply.
TOPS Test	Verify freedom of movement of the turbine control valves	Weekly. Move each of the turbine valves through the cycle. Performed by a control room operator with an observer at the valve.	To avoid a reactor trip, the steam flow to the turbine must be reduced by reducing reactor power or by dumping steam to the condenser.	Caused a significant number of reactor trips. Causes wear to the valves and stress to the steam system.	Turbine overspeed protection is redundant and diverse: mechanical overspeed protection and electrical overspeed protection are provided.
Control Rod Movement Test	Verify that control rods are movable in response to a scram signal	Weekly. Move the control rod at least one notch.	Require a power reduction to reduce stress on the fuel during movement of rods at intermediate positions.	Caused reactor trips. Significant burden on the operators due to long duration of testing.	A concern exists over the extension of test interval, because stagnant water in the seal area may not be sufficiently flushed.
ESFAS Slave Relay Test	Verify the functionality of slave relays.	Quarterly. Involve the actuation of a large number of components (valves and pumps).	A great deal of coordination is necessary between the test technicians and the control room operators	Lead to inadvertent actuations of safety equipments and reactor trips.	Reliability of slave relays themselves is generally good. Those slave relays that offer the greatest potential for plant upsets can be tested during a plant shutdown.

Table 5.2 presents, for the four different kinds of tests, the BWR categories that are associated with the test-caused transients. For example, the performance of a TOPS test may cause the turbine control valve to fail closed to result in the high steam pressure in the main steam system, and consequently, in the turbine trip. Hence, the transient due to the testing can be classified into BWR transient categories 3 and 13, as shown in the table.

(2) Evaluate the risk contributions of the initiating event groups to the total plant risk from the PRA model

The risk contribution of the specific initiating event group, say the j-th initiating event group (i.e., IE-j), to the total plant risk can be easily obtained from the plant-specific PRA model by summing up the frequencies of all the accident sequences beginning from the initiating event group, as shown in Equation (5.3).

For demonstrative applications, we used the PRA[9] for the Peach Bottom Atomic Power Station Unit 2 which was carried out as part of the NUREG-1150 study. Table 5.3 shows the core damage frequency contributions of each initiating event group, R_{IE-j}, for the plant, along with descriptions of the initiating event groups.

(3) Associate transient categories with the plant-specific initiating event groups modeled in the PRA

To use transient categories in the framework of a PRA model, the transient categories should be associated with the initiating event groups modeled in the plant-specific PRA, considering the characteristics of the transients included in the transient categories and the initiating event groups. For this association, we can classify each of the transient categories into the relevant initiating event group.

In Table 5.4, each of the 37 BWR transient categories is associated with the relevant initiating event group for the Peach Bottom Plant. For instance, the transient category 5, main steam isolation valve closure, is classified into the initiating event group T2, which incorporates all the transients that occur with the power conversion system initially unavailable.

(4) Analyze plant operating data to estimate the proportion by which the frequency of the initiating event group is attributable to test-caused transients.

The plant operating data can be used to estimate the proportions, ϕ, by which the initiating event groups are caused from the test-caused transients. According to Equation (5.8) for ϕ, we need to obtain the number of transient events attributable to the given test, N_{test}, along with the number of transients belonging to the initiating event group that is associated with the test-caused transient, N_{IE-j}.

To identify the transient events of interest, analyze the data as follows:

i) Classify the transient events in the data base into the relevant transient categories, identifying the transients caused due to the tests whose risk impacts are being evaluated.

ii) Obtain the number of transient events attributable to each of the given tests, i.e., N_{test}, by adding the numbers of transients in the transient categories which are associated with the test.

iii) Obtain the number of transient events associated with each of the initiating event groups, i.e., $N_{IE\text{-}j}$, by adding the numbers of transients in the transient categories which are associated with the initiating event group.

In this study, the operating data of 30 BWR plants for 1985 were used to obtain the number of the transient events attributable to the four different kinds of tests shown in Table 5.1, and the number of the transients for each of the initiating event groups in the Peach Bottom PRA. The data from the USNRC Gray Books[10] for 1985 were reviewed to identify the transient events and the relevant information, such as the specific plant, the date of the event, and the number of the licensee event report (LER). Since the Gray Books do not provide the detailed information about the transients, such as the specific kinds of testing that caused the plant transient, the information was mostly obtained from the LER system.[11] When such detailed information was not accessible from the LER system, further reference was made to the Nuclear Power Experience data base.[12]

The total number of transient events in the data base, excluding those which occurred while the power was below 25%, was 197. Only these limited data were used for the sake of methodology demonstration, although more data should be used to improve the accuracy of the data analysis results.

Table 5.4 presents the numbers of transient events for each transient category, along with the numbers of test-caused transients which are attributable to the four different kinds of tests. These numbers can be used to obtain the number of transients attributable to each of the given tests, N_{testi}, and the number of transients associated with each of the initiating event groups, $N_{IE\text{-}j}$, as discussed above.

For instance, transient categories 3 and 13 are associated with the TOPS test. Since 6 transients were caused during or as a result of the testing, according to the data analysis as shown in Table 5.4, the number of transients attributable to the test, N_{testi}, is 6. On the other hand, the initiating event group that is associated with the transients due to the TOPS testing is T3A, i.e., the transients with the power conversion system initially available, excluding those due to an inadvertent open relief valve in the primary system and those involving loss of feedwater, but with the steam side of the power conversion system initially available (see Table 5.3). The transient categories associated with T3A are listed in Table 5.4, namely, transient categories 1, 2, 3, 4, 9, etc. The number of transients associated with the initiating event group, N_{T3A}, can be obtained by adding the numbers of transients in the transient categories belonging to the initiating event group. A total of 166 transient events belonging to T3A were identified in the data base as shown in Table 5.5.

The proportions, ϕ, by which the initiating event groups are caused from the associated test-caused transients, can now be estimated using the number of transients attributable to each of the given tests, N_{testi}, and the number of transients associated with each of the initiating event groups, $N_{IE\text{-}j}$, as shown in Equation (5.8). Table 5.5 presents the values of the proportions estimated in this data analysis for the four different kinds of testing.

The data analysis indicates that: (1) 33.3% of the frequency of the initiating event group T2 is attributable to the MSIV operability testing; (2) 3.6% of the frequency of the initiating event group T3A is attributable to the TOPS testing; and (3) 0% of the T3A initiating event group frequency is due to control rod movement testing or ESFAS slave relay testing. The reason for the result of the ϕ value of 0% is that no transient events, which were attributable to either the control rod movement testing or ESFAS slave relay testing, were identified in the analysis of the data based on the operating experience of 30 BWR plants during 1985. Hence, for these two types of testing, more data should be used to get a meaningful result.

Table 5.2 Association of Test-Caused Transients with EPRI BWR Categories

Test	BWR Categories
MSIV Operability Test	6. Inadvertent closure of one MSIV 7. Partial MSIV closure
TOPS Test	3. Turbine trip 13. Turbine bypass or control valves cause increased pressure (closed)
Control Rod Movement Test	27. Rod withdrawal at power 29. Inadvertent insertion of rod or rods
ESFAS Slave Relay Test	35. Spurious trip via instrumentation, RPS fault

Table 5.3 Risk Contributions of the Initiating Event Groups to the Total Core Damage Frequency

Initiator	Description	Risk Contribution R_{IE_j} (per year)
T1	Loss of offsite power (LOSP) transient	6.18E-6
T2	Transient with the power conversion system (PCS) unavailable	5.42E-7
T3	Transient with the PCS initially available made up of T3A, T3B, and T3C	Sum of risk contributions of T3A, T3B, and T3C
T3A	Transients of the T3 group other than those below	1.03E-6
T3B	Transients due to an inadvertent open relief valve in the primary system	4.50E-8
T3C	Transients involving loss of feedwater (LOFW), but with the steam side of the PCS initially available	4.74E-7
A	Large loss of coolant accident (LOCA)	8.38E-6
S1	Intermediate LOCA	8.56E-8

Table 5.4 Association of Transient Categories with Initiators and Results of Data Analysis

Category	Definition	Initiator	Number of Transients	Number of Test-Caused Transients
1	Electric load rejection	T3A	10	
2	Electric load rejection with turbine bypass valve failures	T3A	2	
3	Turbine trip	T3A	11	6
4	Turbine trip with turbine bypass valve failure	T3A	0	
5	Main steam isolation valve closure	T2	3	
6	Inadvertent closure of one MSIV	T2	4	2
7	Partial MSIV closure	T2	2	1
8	Loss of normal condenser vacuum	T2	9	
9	Pressure regulator fails open	T3A	1	
10	Pressure regulator fails closed	T3A	2	
11	Inadvertent opening of a safety/relief valve (stuck)	T3B	1	
12	Turbine bypass fails open	T3A	0	
13	Turbine bypass or control valves cause increased pressure (closed)	T3A	2	0
14	Recirculation control failure, increasing flow	T3A	0	
15	Recirculation control failure, decreasing flow	T3A	1	
16	Trip of one recirculation pump	T3A	3	
17	Trip of all recirculation pumps	T3A	0	
18	Abnormal startup of idle recirculation pump	T3A	0	

Table 5.4. (Cont'd)

Category	Definition	Initiator	Number of Transients	Number of Test-Caused Transients
19	Recirculation pump seizure	T3A	0	
20	Feedwater, increasing flow at power	T3A	4	
21	Loss of feedwater heater	T3A	0	
22	Loss of all feedwater flow	T3C	3	
23	Trip of one feedwater pump (or condensate pump)	T3C	2	
24	Feedwater, low flow	T3C	5	
25	Low feedwater flow during startup or shutdown	T3C	0	
26	High feedwater flow during startup or shutdown	T3A	1	
27	Rod withdrawal at power	T3A	0	0
28	High flux due to rod withdrawal at startup	T3A	0	
29	Inadvertent insertion or rod(s)	T3A	0	0
30	Detected fault in reactor protection system	T3A	0	
31	Loss of offsite power	T1	1	
32	Loss of auxiliary power (or auxiliary transformer)	T3A	11	
33	Inadvertent startup of HPCI/HPCS	T3A	0	
34	Scram due to plant occurrences	T3A	70	
35	Spurious trip via instrumentation, RPS fault	T3A	11	0
36	Manual scram, no out-of-tolerance condition	T3A	37	
37	Cause unknown	T3A	1	

Table 5.5 Test-Caused Risk Contributions from Test-Caused Transients

Test	N_{test}	IE-j	$N_{IE\text{-}j}$	ϕ	$R_{IE\text{-}j}$ (/yr)	R_{trip} (/yr)
MSIV Operability Test	3	T2	9	0.333	5.42E-7	1.81E-7
TOPS Test	6	T3A	166	0.036	1.03E-6	3.72E-8
Control Rod Movement Test	0	T3A	166	0	1.03E-6	0
ESFAS Slave Relay Test	0	T3A	166	0	1.03E-6	0

(5) Evaluate the test-caused risk contributions from test-caused transients

The test-caused risk contribution, R_{trip}, from test-caused transients can now be evaluated by multiplying the risk contribution of the relevant initiating event group to the total plant risk, $R_{IE\text{-}j}$, obtained in step (2), by the proportion ϕ estimated in step (4).

The data analysis indicates that the test-caused risk contributions at core damage frequency level due to transients caused by MSIV operability test and TOPS test are 1.81E-7 and 3.72E-8 per year, respectively. The data analysis results for the other two kinds of testing, i.e., control rod movement testing and ESFAS slave relay testing, should be properly interpreted. As previously discussed, more data should be used to get a meaningful result, especially for these two types of testing, because of the low probability of transients occurring during these tests.

5.4 Development of Additional Formulas with Consideration of Surveillance Test Interval

The formula for the test-caused risk contribution from transients, Equation (5.9), can be rewritten to incorporate test frequency or interval. The advantage of including the test frequency in the formula for the risk impact of test-caused transients, R_{trip}, is that it allows sensitivity studies to be performed for R_{trip} as a function of the test frequency.

This section describes how we can take into account the test frequency in the formulation of the model, and also develops some additional formulas to obtain more insights into the issue of test-caused transients.

5.4.1 Probability of Occurrence of a Test-Caused Transient

Let

τ = the frequency of test-caused transients, (5.10)

f_{test} = the surveillance test frequency, (5.11)

and

p_{trip} = the probability that a transient will occur during or as a result of the given test. (5.12)

The frequency of test-caused transients, τ, can then be expressed in terms of the test frequency and the probability that a transient will occur during a test as:

$$\tau = f_{test} \, P_{trip} \tag{5.13}$$

Equation (5.13) evidently shows that the more frequently the test is conducted, the more transients will occur during a time period due to the test. At the same time, the frequency of the test-caused transients also is proportional to the probability of a transient occurring due to the test. Provided that the test frequency or interval is fixed, the higher the probability of a transient occurring during a test, the more transients the plant will experience during a given time period.

The expected frequency of test-caused transients also can be obtained using the frequency of the initiating event group associated with the test-caused transient, i.e., I_j, and the proportion ϕ by which the initiating event group frequency is attributable to the test-caused transients:

$$\tau = I_j \, \phi \tag{5.14}$$

Equating the two different expressions for the frequency of test-caused transients, τ, Equations (5.13) and (5.14), we can obtain the following expression for the probability of transient occurrence per test, P_{trip}:

$$P_{trip} = \frac{I_j \phi}{f_{test}} \tag{5.15}$$

Since

$$f_{test} = 1 / T \tag{5.16}$$

Equation (5.15) can be expressed in terms of test interval as:

$$P_{trip} = I_j \, T \, \phi \tag{5.17}$$

Equation (5.17) indicates how the probability that a transient will occur during a test can be estimated from the analysis of operating data of nuclear power plants in the framework of a PRA model. The frequency of the j-th initiating event group, I_j, is that used in the PRA model. The test interval, T (or similarly the test frequency, f_{test}), of the given test is for the plants in the data base, and the proportion, ϕ, can be estimated from the data base as discussed in the previous section.

Equation (5.17) should be interpreted cautiously; for instance, it should not be interpreted in such a way that a transient is more likely to occur during a test, as the test interval increases or equivalently the test frequency decreases. The reason for this misinterpretation is that not only the probability, P_{trip}, but also the proportion, ϕ, by which the frequency of the initiating event group is attributable to the test-caused transients, is a function of the test interval, T. The value of ϕ, whose expression is given in Equation (5.8), will generally decrease as the test interval is increased, because fewer transients are expected to occur when fewer tests are performed.

However, if the test interval is extended too long (e.g., 1 year), the probability of a transient occurring during a test may increase, because the plant personnel who perform the test will become less familiar with the testing, and therefore, will be more likely to make errors. In evaluating the surveillance requirements, this kind of qualitative consideration also should be taken into account along with the results of the quantitative risk analysis based on the method presented in this report.

Applying the formula for p_{trip}, Equation (5.17), to the tests used in the previous section, we can obtain the probabilities that a transient will occur during an MSIV operability test and a TOPS test. Based on the assumption of quarterly MSIV operability testing and weekly TOPS testing for all the 30 plants used in the data analysis, the probabilities are 6.67E.2 and 1.66E-3, respectively, as shown in Table 5.6.

Table 5.6 Probability that a Transient will Occur During Testing

Test	I_j (/yr)	T(yr)	P_{trip}
MSIV Operability Test	0.8	1/4	6.67E-2
TOPS Test	2.4	7/365	1.66E-3

The probability of a transient occurring for the MSIV operability test is based on the assumption of quarterly testing, as defined in standard Technical Specification, i.e., 3 months of test interval, for all the 30 plants. If we consider the specific test intervals for the plants, the probability may become lower, because some plants test the MSIVs more often than quarterly, and as a result, the value of T in Equation (5.17) will be less than 3 months.

5.4.2 Formula for the Test-Caused Risk Contribution from Transients in Terms of Test Interval

From Equation (5.17), we have an expression for the proportion, ϕ, by which the initiating event group frequency is attributable to the test-caused transients:

$$\phi = \frac{P_{trip}}{I_j\,T} \tag{5.18}$$

An alternate formula for the test-caused risk contribution from test-caused transients, R_{trip}, can then be obtained in terms of test interval by substituting Equation (5.18) into Equation (5.6):

$$R_{trip} = \frac{P_{trip}}{I_j\,T}\,R_{IE-j} \tag{5.19}$$

Equation (5.19) can be used to establish criteria on the test interval for risk-effectiveness of the test. Also, sensitivity studies can be performed to observe the sensitivity of R_{trip} to the variation of T, based on the assumption that the probability of a transient occurring during a test is constant.

5.4.3 Alternate Derivation of the Formula for the Test-Caused Risk Contribution from Transients

The formula for the test-caused risk contribution from transients in terms of test interval, i.e., Equation (5.19), can be derived in an alternate manner. The alternate derivation of the formula will provide additional insight into the test-caused risk contribution from transients.

Assume the conduction of the given test causes a transient with a probability of p_{trip}. When a transient occurs, the probability that a core damage will result is $\hat{R}_1(\text{trip})$:

$\hat{R}_1(\text{trip})$ = the probability that core damage will occur as a result of the transient. (5.20)

$\hat{R}_1(\text{trip})$ is calculated by isolating the sequences in a PRA initiated by the transient, or the initiating event group associated with the transient, and then setting the frequency equal to 1 to determine the resulting core damage probability. (The subscript "1" in $\hat{R}_1(\text{trip})$ denotes that the trip frequency is set to 1.) Note that the result is a core damage probability and not a core damage frequency, because the frequency is set equal to 1.

Thus, the risk contribution, $\hat{R}_{trip}$, associated with the possibility of test-caused transients is:

$$\hat{R}_{trip} = p_{trip}\,\hat{R}_1(\text{trip}). \tag{5.21}$$

Specifically, $\hat{R}_{trip}$ is the core damage probability contribution associated with test-caused transients.

The core damage frequency contribution, R_{trip}, associated with test-caused transients is $\hat{R}_{trip}$ divided by the test interval T, i.e.:

$$R_{trip} = \frac{p_{trip}}{T}\,\hat{R}_1(\text{trip}) \tag{5.22}$$

Equation (5.22) is identical to Equation (5.19), because the ratio of $R_{IE\text{-}j}$ to I_j in Equation (5.19) can also be interpreted in a similar manner as $\hat{R}_1(\text{trip})$, i.e., as the probability that a core damage will occur provided that the conduction of the test causes a transient. Thus, we obtain the following expression for the conditional core damage probability, $\hat{R}_1(\text{trip})$:

$$\hat{R}_1(\text{trip}) = \frac{R_{IE\text{-}j}}{I_j} \tag{5.23}$$

5.5 Risk-Effectiveness Evaluation With Regard to Test-Caused Transients

5.5.1 Use of the General Formula for R_{trip} Without Test Interval

As discussed in Section 2, the test is risk-effective if the risk contribution detected by the test, R_D, is greater than the risk contribution caused by the test, R_C:

$$R_D > R_C : \quad \text{risk-effective test} \tag{5.24}$$

Substituting the equation for R_C, developed in Section 3, i.e., Equation (3.2), into Equation (5.24) we have

$$R_D > R_{trip} + R_{wear} + R_{state} + R_{down} \tag{5.25}$$

Some contributions in the right-hand side of the equation will not be relevant nor significant in any specific case as previously discussed.

Suppose that only the contribution due to test-caused transients, R_{trip}, is predominant among the many contributions listed in the right-hand side of Equation (5.25). The criteria for risk effectiveness can then be represented as:

$$R_{trip} < R_D: \quad \text{test risk-effective (with regard to test-caused transients)} \tag{5.26}$$

The risk-effectiveness of the test can be evaluated using Equation (5.26) with regard to test-caused transients, even if some of the risk contributions other than R_{trip} are not insignificant compared to R_{trip}.

The risk contribution detected by a test, R_D, can be evaluated using a PRA model as described in Section 4:

$$R_D = \frac{\lambda T}{2}(R_1 - R_0) \tag{5.27}$$

On the other hand, the test-caused risk contribution due to test-caused transients, R_{trip}, can be evaluated by analyzing plant operating data in the framework of a PRA model, as discussed in Section 5.2

Inserting Equations (5.27) and (5.6) into Equation (5.26), we obtain the following criteria for risk-effectiveness with regard to test-caused transients:

$$\phi\, R_{IE-j} < \frac{\lambda T}{2}(R_1 - R_0): \quad \begin{array}{l}\text{test risk-effective with regard}\\ \text{to test-caused transients}\end{array} \tag{5.28}$$

Equation (5.28) can be applied to the MSIV operability test and the TOPS test to see whether or not the tests are risk-effective with regard to test-caused transients. However, because turbine control valves are not specifically modeled in the PRA for the Peach Bottom Plant, the risk benefit, especially the core damage frequency when the turbine control valve is assumed to be up or down, i.e., R_0 and R_1, cannot be estimated. Accordingly, the risk-effectiveness of the TOPS testing is not discussed here.

Applying the formula for R_D, Equation (5.27), to the MSIV operability testing, we obtain the test-detected core damage frequency contribution: $R_D = 5.18E\text{-}7$ per year. The test-caused core damage frequency contribution, R_{trip}, for the test was estimated as shown in Table 5.5: $R_{trip} = 1.81E\text{-}7$ per year. Since the test-detected risk contribution is larger than the test-caused risk contribution due to transients, the MSIV operability test is risk-effective with regard to test-caused transients.

However, one should take the following into consideration, in interpreting the result of the risk-effectiveness evaluation:

(1) The test-caused risk contribution due to transients for the MSIV operability test was estimated, based on the value of the probability of a transient occurrence which was obtained using the operating experience of 30 reactor years. Only 3 transient events due to the MSIV testing were identified in the operating data base, among the 9 transient events belonging to the relevant initiating event group, T2, as shown in Table 5.5. Hence, more data evaluations should be performed to establish an estimate of the probability of occurrence of a test-caused transient during the MSIV operability test.

(2) The MSIV operability testing was assumed to be conducted quarterly for each of the 30 BWR plants used in the data analysis. However, it appears that this is not always the case; e.g., the LER by Quad Cities 2 plant, which describes the transient event that took place during a MSIV test, indicates that operators were performing a biweekly MSIV operability surveillance (see Appendix A). To simplify the analysis for methodology demonstration, the surveillance test interval for each of the 30 plants was not specifically taken into account; instead, the analysis was performed with the assumption of quarterly MSIV operability testing for all the plants.

5.5.2 Use of the Alternate Formula for R_{trip} with Test Interval

The criteria for risk-effectiveness of tests also can be established using the alternate formula for the test-caused risk contribution due to test-caused transients, R_{trip}, i.e., Equation (5.19), which incorporates the test interval.

Substituting formulas for R_{trip} and R_D, Equations (5.19) and (5.27), into Equation (5.26) we have:

$$\frac{p_{trip}}{I_j T} R_{IE\text{-}j} > \frac{\lambda\ T}{2}(R_1 - R_0): \qquad \text{test risk-ineffective with regard to test-caused transients} \qquad (5.29)$$

Equation (5.29) can be used to set a criterion on the test interval, T, for risk-ineffective tests. Using Equation (5.29), the test is risk-ineffective if:

$$\frac{\lambda T^2}{2} < \frac{p_{trip}}{I_j} \frac{R_{IE-j}}{R_1 - R_0}; \quad \text{test risk-ineffective with regard to test-caused transients} \tag{5.30}$$

Hence, the test is risk-ineffective if:

$$T < \sqrt{\frac{2\, p_{trip}}{\lambda\, I_j} \frac{R_{IE-j}}{R_1 - R_0}}; \quad \text{test risk-ineffective with regard to test-caused transients} \tag{5.31}$$

Criteria can also be established for test intervals to ensure that they are not too short so as to be risk-ineffective, but instead are risk-effective. From Equation (5.31), the test will be risk-effective with regard to test-caused transients if:

$$T > \sqrt{\frac{2\, p_{trip}}{\lambda\, I_j} \frac{R_{IE-j}}{R_1 - R_0}}; \quad \text{test risk-effective with regard to test-caused transients} \tag{5.32}$$

Again, ratios or only relative considerations enter into the criterion.

The risk-effectiveness criteria on the test interval, Equations (5.31) and (5.32), should be used only when the probability of a transient occurrence, p_{trip}, can be reasonably estimated. To obtain a reasonable estimate of p_{trip}, it is necessary to use sufficient operating data. The less likely a test-caused transient occurs, the more operating data will become necessary, in general, to reasonably estimate the probability of occurrence of a test-caused transient.

Let

T_{min} = the minimum test interval such that the test is risk-effective with regard to test-caused transients, as long as the test interval is greater than the minimum test interval. (5.33)

The minimum test interval, T_{min}, can then be obtained from the following equation:

$$T_{min} = \sqrt{\frac{2\, p_{trip}}{\lambda\, I_j} \frac{R_{IE-j}}{R_1 - R_0}} \tag{5.34}$$

Equation (5.34) also should be applied only when a reasonable estimate of the probability of a transient occurrence, p_{trip}, is available through the use of sufficient data.

We can note from Equation (5.34) the following:

(1) As a transient is more likely to occur during a test, the surveillance test interval should be increased.

(2) As the risk benefit of a test, which is proportional to $(R_1 - R_0)$, is smaller, the test interval should be extended.

Although these are not new concepts, Equation (5.34) shows that these simple concepts can be proved from a quantitative risk point of view.

Applying Equation (5.34) to the MSIV operability test, we have: T_{min} = 54 days. Since the test interval of the MSIV operability testing, i.e., 3 months, is greater than the minimum test interval, the test is risk-effective with regard to the test-caused transients. However, the assumptions discussed earlier in this section should be considered in interpreting the result.

5.6 Sensitivity Analyses

Sensitivity studies were performed to evaluate the sensitivity of the risk contribution associated with test-caused transients, R_{trip}, to some of the parameters affecting the value of R_{trip}. Figure 5.1 shows the sensitivity of R_{trip} to the variation in the proportion, ϕ, by which the initiating event group frequency is attributable to the test-caused transients. The value of R_{trip} is equal to the value of $R_{IE\text{-}j}$, if the initiating event group frequency is only due to the test-caused transients, i.e., if ϕ is 1. In such a case, the values of R_{trip} will be 5.4E-7 and 1.0E-6 per year for the MSIV operability testing and the TOPS testing, respectively, which are the maximum values of the two lines in Figure 5.1.

However, only 33.3% and 3.6% of the frequencies of the relevant initiating event groups were found from the data analysis to be attributable to the test-caused transients, as presented in Table 5.5. Thus, the risk impact due to transients, R_{trip}, is 1.8E-7 and 3.7E-8 per year for the MSIV operability test and the TOPS test, respectively, as shown by dotted lines in Figure 5.1. The R_{trip} value is slightly more sensitive to the variation in the ϕ value for the TOPS test as compared to the MSIV operability test, although the difference is not clearly visible in Figure 5.1. (The slope of the sensitivity line for the TOPS test is 1.0E-6, while it is 5.4E-7 for the MSIV test.)

Figure 5.2 shows how the test-caused risk contribution from transients will vary depending on the number of test-caused transients, N_{test}, for the given number of transient events belonging to the relevant initiating event group. The R_{trip} value is more sensitive to N_{test} for the MSIV operability test as compared to the TOPS test. (The slopes of the sensitivity lines are 6.0E-8 and 6.2E-9 for the MSIV test and the TOPS test, respectively.)

The dotted lines in Figure 5.2 indicate the specific result of the data analysis performed in this study. For instance, only 3 transient events were found in the operating data base of 30 reactor years for the MSIV operability testing, and the corresponding risk impact is 1.8E-7 per year. If 2 or 4 transients were found in the data base, the risk impact due to the test-caused transients would be 1.2E-7 and 2.4E-7 per year, respectively. From Figure 5.2, we can also see that the risk impact due to test-caused transients spans approximately 1 order of magnitude for the MSIV operability testing and about 2 orders of magnitude for the TOPS testing.

The most useful result of the sensitivity study for risk-effectiveness evaluation of surveillance requirements is presented in Figure 5.3. This figure shows, for the MSIV testing, the sensitivity of the following three different kinds of risk impacts to the variation of the test interval, T: (1) the test-caused risk contribution due to transients, R_{trip}, (2) the test-detected contribution, R_D, and (3) the total risk impact of the test, R_T, which is the sum of R_{trip} and R_D (refer to Section 2).

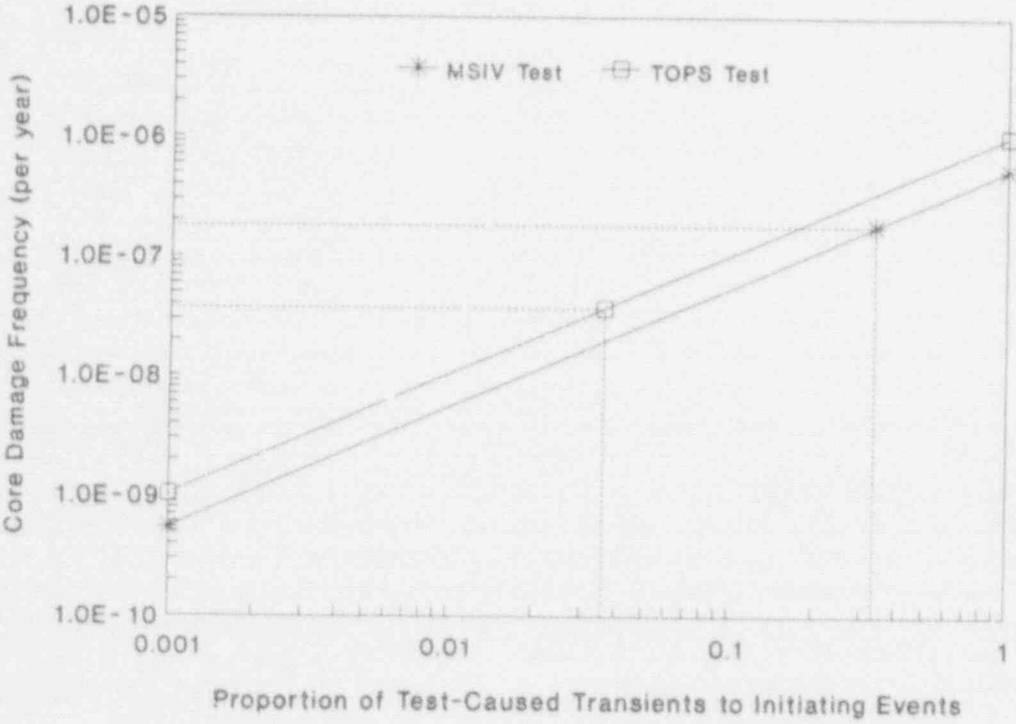


Figure 5.1 Sensitivity of the test-caused core damage frequency impact, R_{trip}, to the proportion of test-caused transients to initiating events, ϕ.

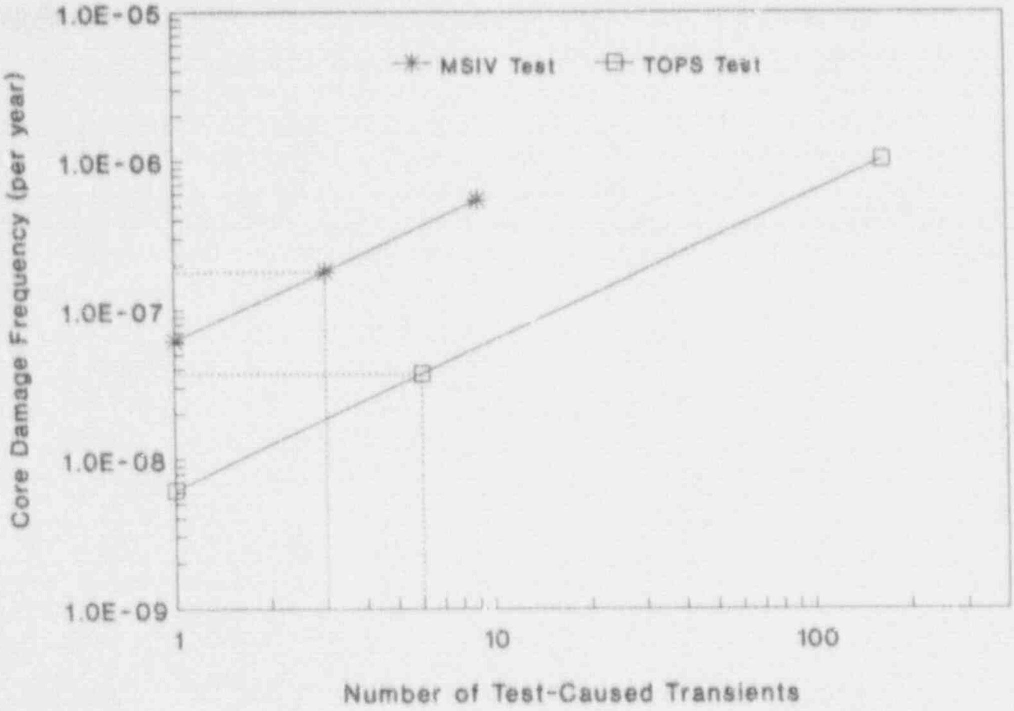


Figure 5.2 Sensitivity of the test-caused core damage frequency impact, R_{trip}, to the number of test-caused transients, N_{test}.

From Figure 5.3, we can obtain the following insights and conclusions:

(1) R_{trip} decreases as T is increased, because less transients are expected to occur as the test is conducted less frequently (see Equation (5.19)). However, R_D increases with the increasing test interval, because the test is more likely to detect a failure in such a case (refer to Equation (5.27)).

(2) The intersection between the two curves for R_D and R_{trip} occurs when the test interval is approximately 54 days. The test interval at this intersection is the minimum test interval, T_{min}, which was previously discussed (see Equations (5.33) and (5.34)). From the point of view of T_{min}, the test interval must be longer than 54 days for the MSIV testing to become risk-effective, otherwise the test will be risk-ineffective.

(3) The risk-effectiveness of the test with regard to test-caused transients also can be seen by comparing the test-detected risk contribution to the test-caused risk contribution due to transients. In the region where $T > 54$ days, R_D is larger than R_{trip}. Thus, the test is risk-effective in this region. In the other region where $T < 54$ days, the test is risk-ineffective. If the test is conducted every 54 days, it is risk neutral.

(4) An important conclusion relevant to the redefinition of a standard test interval is that the interval for the MSIV operability testing, i.e., 91 days, can be extended without undue increase in the risk impact. For example, if the test interval is extended to 150 days, R_D increases because the test is more likely to detect failures, while R_{trip} decreases because less testing during a given time period will result in less transients, as discussed in item (1) above. However, as shown by a dotted curve in Figure 5.3, the total risk impact of the test, R_T, only marginally increases, when T is changed from 91 days to 150 days. (R_T increases from 6.99E-7 per year to 9.64E-7 per year.)

(5) In this study, the LER data base for 30 BWRs for 1985 were used, with the assumption that the operability of MSIVs is tested quarterly at all the plants, as we discussed. However, the data analysis revealed that some plants test the operability of MSIVs more frequently; e.g., the operators of Quad-Cities Nuclear Power Station, Unit 2, were performing biweekly MSIV operability surveillance when the test failure occurred in the plant as shown in Appendix A. If we assume that the minimum test interval of 54 days is also applicable to this plant, we can say that the biweekly test is risk-ineffective with regard to test-caused transients, because the test interval is shorter than 54 days. Even if we consider other types of adverse risk impacts and they are not negligible compared to R_{trip}, the test will be risk-ineffective.

(6) The result of sensitivity analyses, such as that shown in Figure 5.3, can be very useful in defining test intervals. However, it should be carefully interpreted. In Figure 5.3, the sensitivity curves of R_{trip} and R_T to the variation of T are based on the assumption that the probability, p_{trip}, of a transient occurring during testing is constant. However, the value of p_{trip} may change (tend to increase), especially when the test is conducted far less frequently than it used to be, because the operators are more likely to make errors. Therefore, when considering an extension of test interval based on the sensitivity analyses, one should not prolong the test interval too much, e.g., by more than a factor of two. The degree, by which the test interval may be extended, mainly depends on the likelihood that p_{trip} will vary following the change of the test frequency.

A sensitivity study also was performed for the TOPS testing. Figure 5.4 shows the sensitivity of R_{trip} to T. The test-detected risk contribution, R_D, could not be estimated from the PRA for the Peach Bottom Plant, since the turbine control valves were not modeled in the PRA. Hence, only the quantitative values of R_{trip} and p_{trip} can be taken into account in evaluating the test, unless the value of R_D, specifically R_0 and R_1, is obtained following the modification of the PRA model.

Comparing the curve of R_{trip} for the MSIV operability testing to that for the TOPS testing, we can see a similar trend of sensitivity to the variation in the test interval. However, the adverse risk impact from the MSIV test is higher by approximately 2 orders of magnitude than that from the TOPS test. Hence, we can see, from a point of view of quantitative risk evaluation, that the TOPS test generates much less risk from test-caused transients than the MSIV operability test does.

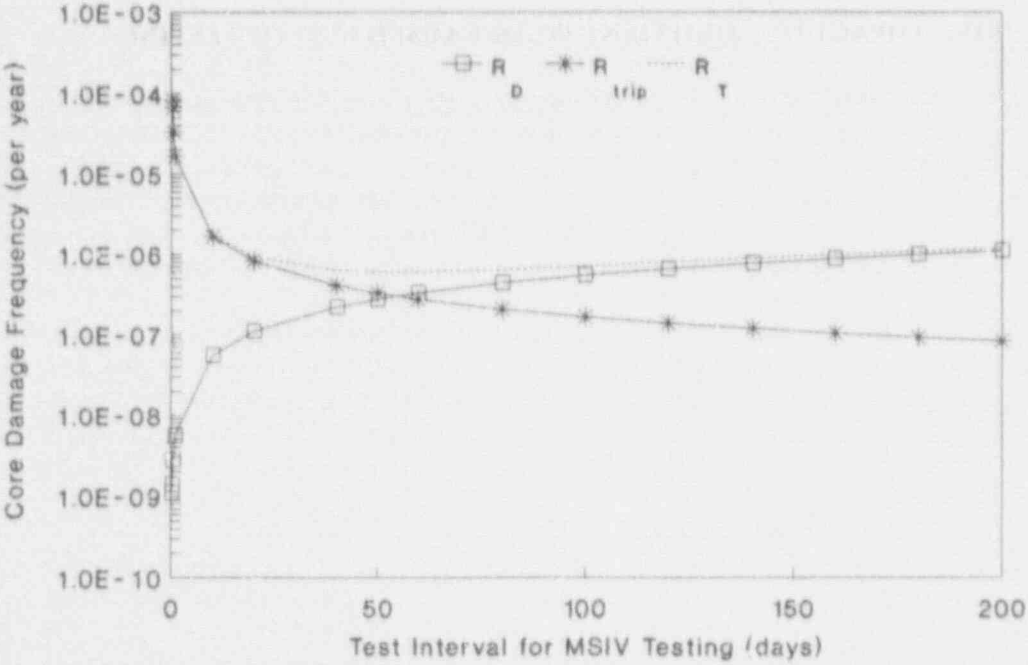


Figure 5.3 Sensitivity of the core damage frequency impact to the test interval for the main steam insolation valve testing (R_D = test-detected risk impact; R_{trip} = test-caused risk impact due to transients; R_T = total risk impact of the test)

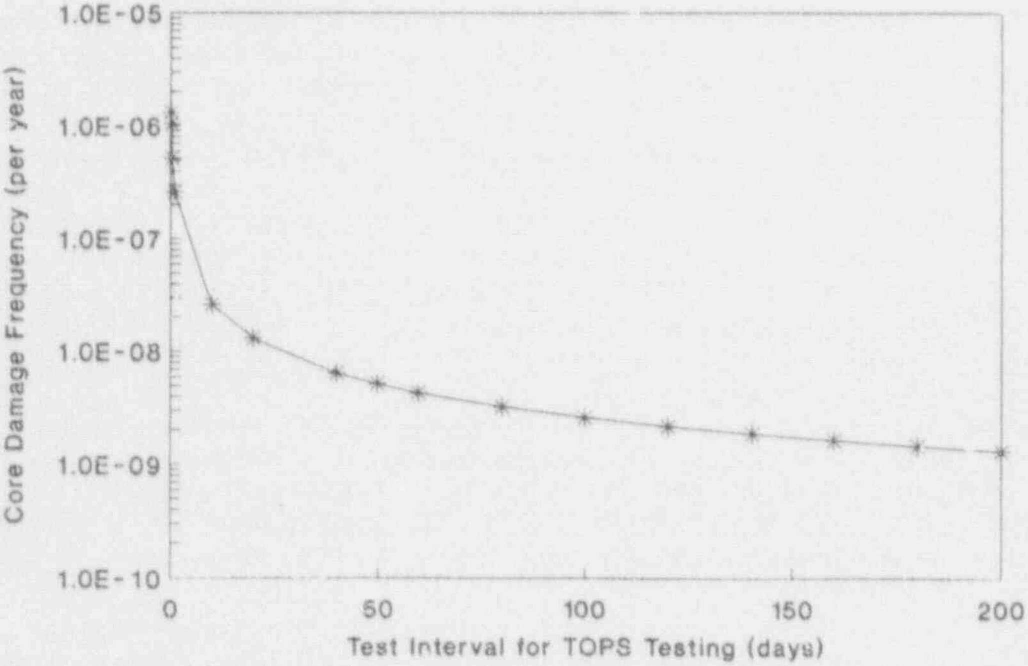


Figure 5.4 Sensitivity of the test-caused core damage frequency impact due to test-caused transients, R_{trip}, to the test interval for the turbine overspeed protection system testing

6. RISK IMPACT OF EQUIPMENT WEAR CAUSED DUE TO TESTING

We shall consider the risk contribution associated with test-caused equipment wear, as another specific test-caused risk contribution. Section 6.1 presents test-caused degradation models for a component in terms of its unavailability. Once the component unavailability is obtained, it can then be used to evaluate the risk impact of the test-caused degradation. The models explicitly incorporate the number of tests performed on the component as a variable to account for the progressive component wear-out due to periodic tests.

Section 6.2 then discusses the formulas for evaluating the risk impact of test-caused component degradations, along with the criteria for the risk-effectiveness evaluation with regard to test-caused degradation. Section 6.3 presents the assumptions and limitations of the models and formulas developed in Sections 6.1 and 6.2. Section 6.4 addresses the estimation of parameters and the results of sensitivity analyses on the test-caused degradation effects.

6.1 Test-Caused Component Degradation Models

6.1.1 Concept of Stress on the Equipment

In nuclear power plants, safety-significant components such as a diesel generator or an auxiliary feedwater pump are tested so often--generally monthly and more often in certain situations--that the tests may lead to progressive wear-out of the equipment due to the accumulation of degradation effects caused by testing. Furthermore, the component will also suffer from aging effects, such as corrosion or erosion, as time passes.

The accumulating test-caused degradation and aging effects will increase the unavailability of the component, and thereby the unavailability of the associated safety system and function. The increase in the safety system or function unavailability will then reduce the plant's accident mitigating capability.

From a viewpoint of stress on the component, the test-caused component degradations and aging effects are induced by two kinds of stresses, i.e., demand and standby stresses.[13] Demand stress (or cycle-related stress) acts on equipment only when the equipment is asked to function or is operating. Standby stress (or time-related stress) acts on equipment while it is in the standby state. For standby components which are periodically tested, it is generally the combination of both stresses that causes the equipment to degrade, and ultimately to fail.

Component failures may occur sometime during the standby period, upon a demand for operation, or sometime during operation after successful demand. Note that the failure occurring sometime during operation after successful demand may be considered as being due to operation stress. However, the operation stress is considered as being part of the demand stress.

To illustrate how both stresses act together to result in an equipment failure, let us take an example from a diesel generator reliability study.[13] Consider the case that a connecting rod, weakened by corrosion, fails catastrophically during diesel operation. This failure was caused certainly by standby stress, which induced the corrosion of the rod. However, it also was caused by demand stress, because although the rod was in a weak state due to standby stress, it would not have failed if there had been no demand for operation.

6.1.2 Formulation of the Basic Component Degradation Model and its Exploration

Based on the concept of stress previously discussed, a test-caused component degradation model can be formulated. From a risk standpoint, the risk parameter that is directly affected by the degradation mechanism is the component failure rate and unavailability. The component degradation model will be developed in terms of unavailability rather than failure rate, because the unavailability encompasses the failure rate and also is more directly applicable to the risk quantification.

The time-dependent unavailability, $q(t)$, of a component is standardly expressed as:[14]

$$q(t) = 1 - \exp\left[-\int_0^t \lambda'(t')dt'\right] \tag{6.1}$$

where the failure rate λ' includes the contributions from both demand and standby stresses.

Expanding the exponential term of Equation (6.1) by Taylor's formula and taking only the first-order expansion, we have:

$$q(t) = \int_0^t \lambda'(t')dt' \tag{6.2}$$

This expression is a valid first-order approximation for the usual case, where the integration of the failure rate over time is less than 0.1.

To evaluate the risk impact associated with test-caused equipment degradations, it is necessary to model the demand stress separately from the standby stress. Since the demand stress acts on the equipment only when the demand is imposed on it, the contribution of the demand stress to the component unavailability can be taken out of the integration in Equation (6.2) as follows:

$$q(n,t) = \rho(n) + \int_{nT}^{nT+t} \lambda(n,t')dt' \qquad \text{for } t \in [0,T] \tag{6.3}$$

where

n = the number of tests performed on the equipment,
t = the time elapsed since the last test,
$\rho(n)$ = the failure probability for demand caused failures,
$\lambda(n,t)$ = the standby failure rate (per unit time) for failures occurring between tests,
T = the test interval, and
$nT + t$ = the time since the last renewal point.

Note in Equation (6.3) the unavailability, q, and the standby failure rate, λ, are represented as a function of the number of tests performed on the equipment, n, as well as the chronological time, t. The reason for the functional notation of λ is that the standby failure rate is assumed to be affected by not only the standby time, but also the test-caused degradation effect. As a result, the component unavailability becomes a function of the number of tests performed on the component since the last renewal point as well as the time elapsed since the last renewal. However, the demand failure probability, ρ, is represented in Equation (6.3) as a function of only the number of tests, n, i.e., it is assumed that the demand failure probability depends only on how many tests have been conducted on the component.

Let us now formulate expressions for the two basic degradation parameters, $\rho(n)$ and $\lambda(n,t)$, in terms of their variables n and t. First, for the demand failure probability, $\rho(n)$, the following expression can be formulated as a function of the number of tests, n, since the last overhaul point:

$$\rho(n) = \rho_0 + \rho_0 f_1^{\beta_1} \tag{6.4}$$

where

ρ_0 = residual demand-failure probability,
$f_1 = p_1 n$,
p_1 = test degradation factor associated with demand failures, and
β_1 = test impact parameter associated with demand failures.

The residual demand failure probability, ρ_0, is included in Equation (6.4) to reflect the fact that even a new component, i.e., $n = 0$ and $t = 0$, may fail when a demand for operation is placed on the component. The test-caused degradation factor, p_1, accounts for the test-caused degradation due to demand stress.

The standby failure rate, $\lambda(n,t)$, can next be formulated as a function of the number of tests, n, and the time, t, as follows:

$$\lambda(n,t) = \lambda_0 + \lambda_0 f_2^{\beta_2} + \alpha u^{\beta_3} \qquad \text{for } t \in [0,T],\ u \in [0,nT+t] \tag{6.5}$$

where

λ_0 = residual standby time-related failure rate,
$f_2 = p_2 n$,
p_2 = test degradation factor for standby time-related failures,
β_2 = test impact parameter associated with standby time-related failures,
α = aging factor associated with pure aging, and
β_3 = aging impact parameter associated with aging-related failures.

The test degradation factor, p_2, accounts for the test-caused degradation due to standby stress. A major difference between Equations (6.4) and (6.5) is the existence of the third term in Equation (6.5), i.e., αu^{β_3}. This term is included as a separate contributor to the standby failure rate to reflect the fact that the standby failure rate increases as the component ages in time, even if no tests are carried out on the component. The aging factor, α, and aging impact parameter, β_3, of the term account for the aging, i.e., pure aging as distinct from the test-caused degradations. Note in Equation (6.5) that the time, t, is measured from the time when the last test was performed, whereas the time, u, is measured from the last overhaul point.

The formulas developed for the demand failure probability, $\rho(n)$, and the standby failure rate, $\lambda(n,t)$, i.e., Equations (6.4) and (6.5), include many parameters, all the values of which can not be easily estimated based on the data that are typically available. To facilitate the estimation of parameters, we can linearize the model as follows by setting β_1, β_2, and β_3 equal to 1:

$$\rho(n) = \rho_0 + \rho_0 f_1 \tag{6.6}$$

$$\lambda(n,t) = \lambda_0 + \lambda_0 f_2 + \alpha u \qquad \text{for } t \in [0,T],\ u \in [0,nT+t] \tag{6.7}$$

We will use hereafter this linear component degradation model, i.e., Equations (6.3), (6.6), and (6.7).

The linear model can be re-expressed in terms of t_0, which is the time when n tests have been performed, i.e., $t_0 = nT$, instead of the number of tests, n:

$$q(t_0,t) = \rho(t_0) + \int_{t_0}^{t_0+t} \lambda(t_0,t')\, dt' \tag{6.8}$$

$$\rho(t_0) = \rho_0 + \rho_0 p_1 \frac{t_0}{T} \tag{6.9}$$

$$\lambda(t_0,t) = \lambda_0 + \lambda_0 p_2 \frac{t_0}{T} + \alpha u \qquad \text{for} \quad t \in [0,T],\ u \in [0,t_0+t] \tag{6.10}$$

Based on these basic expressions, i.e., Equations (6.8) to (6.10), the component degradation model can now be developed for various specific circumstances. First, the model will be explored for the following four different cases:

(1) Without test-caused degradation and aging effects
(2) With aging effect but without test-caused degradation effect
(3) With test-caused degradation effect but without aging effect
(4) With both test-caused degradation and aging effects

Special considerations will then be given to unavailability doubling time and component renewal.

Component Degradation Model Without Test-Caused Degradation and Aging Effects

The simplest degradation model is the one which accounts for neither of the test-caused degradation effect nor the aging effect. This model can be obtained noting the parameters associated with the test-caused degradation and aging effects, and then setting them equal to zero.

Among the parameters explored earlier, the test degradation factors, p_1 and p_2, account for the test-caused degradation effect, while the aging factor, α, accounts for the aging effect. Hence, setting these factors to zero in Equations (6.9) and (6.10) we have:

$$\rho(t_0) = \rho_0 \tag{6.11}$$

$$\lambda(t_0,t) = \lambda_0 \qquad \text{for} \qquad t \in [0,T] \tag{6.12}$$

Inserting Equations (6.11) and (6.12) into Equation (6.3) then yields the following expression for time-dependent component unavailability that does not take into account the test-caused degradation and aging effects:

$$q(t) = \rho_0 + \int_{t_0}^{t_0+t} \lambda_0 \, dt' \qquad \text{for } t \in [0,T]$$

$$= \rho_0 + \lambda_0 t \tag{6.13}$$

The average unavailability, $\bar{q}$, in the time period of a surveillance interval, T, and the instantaneous unavailability at time T, i.e., q(T), can then be estimated by:

$$\bar{q} = \frac{1}{T} \int_0^T q(t')dt' = \rho_0 + \frac{1}{2}\lambda_0 T \tag{6.14}$$

$$q(T) = \rho_0 + \lambda_0 T \tag{6.15}$$

<u>Component Degradation Model With Aging Effect but Without Test-Caused Degradation Effect</u>

When test-caused degradation effects are not taken into account, we obtain the following expressions for the demand failure probability and the standby failure rate by setting the test degradation factors, p_1 and p_2, to zero in Equations (6.9) and (6.10):

$$\rho(t_0) = \rho_0 \tag{6.16}$$

$$\lambda(t_0,t) = \lambda_0 + \alpha u \qquad \text{for} \qquad t \in [0,T],\ u \in [0,t_0+t] \tag{6.17}$$

Substituting these two expressions into Equation (6.8) gives the component degradation model in this case:

$$q(t_0,t) = \rho_0 + \int_{t_0}^{t_0+t} (\lambda_0 + \alpha u)du$$

$$= \rho_0 + \lambda_0 t + \frac{\alpha}{2}(2t_0 t + t^2) \tag{6.18}$$

The average unavailability in the time period between t_0 and $t_0 + T$, $\bar{q}(t_0)$, and the instantaneous unavailability at $t = t_0 + T$, $q(t_0,T)$, can be evaluated by:

$$\bar{q}(t_0) = \frac{1}{T}\int_0^T q(t_0,t)\,dt$$

$$= \rho_0 + \frac{1}{2}\lambda_0 T + \frac{\alpha}{2}(t_0 T + \frac{T^2}{3}) \tag{6.19}$$

$$q(t_0,T) = \rho_0 + \lambda_0 T + \frac{\alpha}{2}(2t_0 T + T^2) \tag{6.20}$$

Component Degradation Model With Test-Caused Degradation Effect But Without Aging Effect

In this case, we can set the aging factor, α, equal to zero. Equations (6.9) and (6.10) then become:

$$\rho(t_0) = \rho_0 + \rho_0 p_1 \frac{t_0}{T} \tag{6.21}$$

$$\lambda(t_0,t) = \lambda_0 + \lambda_0 p_2 \frac{t_0}{T} \tag{6.22}$$

Inserting Equations (6.21) and (6.22) into Equation (6.8) yields the following component degradation model in this case:

$$q(t_0,t) = \rho_0 + \rho_0 p_1 \frac{t_0}{T} + \lambda_0 t(1 + p_2 \frac{t_0}{T}) \tag{6.23}$$

Equation (6.23) can be expressed as:

$$q(t_0,t) = q(t) + \frac{t_0}{T}(\rho_0 p_1 + \lambda_0 p_2 t) \tag{6.24}$$

where the expression for q(t), i.e., Equation (6.13), was used.

The average unavailability in the time period between t_0 and $t_0 + T$, $\bar{q}(t_0)$, and the instantaneous unavailability at $t = T$, $q(t_0,T)$, can then be estimated as follows:

$$\bar{q}(t_0) = \bar{q} + \rho_0 p_1 \frac{t_0}{T} + \frac{1}{2}\lambda_0 p_2 t_0 \tag{6.25}$$

$$q(t_0,T) = q(T) + \frac{t_0}{T}(\rho_0 p_1 + \lambda_0 p_2 T) \tag{6.26}$$

in which $\bar{q}$ and q(T) are given by Equations (6.14) and (6.15), respectively.

Con[illegible] Degradation Model With Both Test-Caused Degradation and Aging Effects

Thus far, the component degradation model has been developed accounting for none or only one of the two kinds of degradation effects, i.e., test-caused degradation and aging effects. However, both effects should be taken into account, in general, i.e., to evaluate the unavailability or risk impact associated with test-caused degradations after a long period of time, because aging effects are not negligible in such a case.

To incorporate both test-caused degradation and aging effects, the expressions for the demand failure probability, $\rho(t_0)$, and the standby failure rate, $\lambda(t_0,t)$, in Equations (6.9) and (6.10) can be used without any simplification. Substituting Equations (6.9) and (6.10) into Equation (6.8), we can obtain the most comprehensive time-dependent component degradation model:

$$q(t_0,t) = q(t) + \rho_0 p_1 \frac{t_0}{T} + p_2 \lambda_0 \frac{t_0}{T}\, t + \frac{\alpha}{2}\,(2 t_0 t + t^2) \tag{6.27}$$

where q(t) is given in Equation (6.13).

The average unavailability in the time period between t_0 and $t_0 + T$, $\bar{q}(t_0)$, and the instantaneous unavailability at $t = T$, $q(t_0,T)$, are then given by:

$$\bar{q}(t_0) = \bar{q} + p_1 \rho_0 \frac{t_0}{T} + \frac{1}{2}\, p_2 \lambda_0 t_0 + \frac{\alpha}{2}\,\left(t_0 T + \frac{T^2}{3}\right) \tag{6.28}$$

$$q(t_0,T) = q(T) + p_1\rho_0\frac{t_0}{T} + p_2\lambda_0 t_0 + \frac{\alpha}{2}(2t_0T + T^2) \tag{6.29}$$

where $\bar{q}$ and $q(T)$ are given in Equations (6.14) and (6.15), respectively.

The above formulas for time-dependent, average, and instantaneous unavailabilities, i.e., Equations (6.27) to (6.29), can be rewritten as:

$$q(t_0,t) = q(t) + \Delta q(t_0,t) \tag{6.30}$$

$$\overline{q}\ (t_0) = \overline{q} + \Delta\overline{q}\ (t_0) \tag{6.31}$$

$$q(t_0,T) = q(T) + \Delta q(t_0,T) \tag{6.32}$$

where $q(t)$, $\bar{q}$, and $q(T)$ are given in Equations (6.13) to (6.15), respectively, and

$$\Delta q(t_0,t) = p_1\rho_0\frac{t_0}{T} + p_2\lambda_0\frac{t_0}{T}\ t + \frac{\alpha}{2}(2t_0t + t^2) \tag{6.33}$$

$$\Delta\bar{q}(t_0) = p_1\rho_0\frac{t_0}{T} + \frac{1}{2}p_2\lambda_0 t_0 + \frac{\alpha}{2}(t_0T + \frac{T^2}{3}) \tag{6.34}$$

$$\Delta q(t_0,T) = p_1\rho_0\frac{t_0}{T} + p_2\lambda_0 t_0 + \frac{\alpha}{2}(2t_0T + T^2) \tag{6.35}$$

The $\Delta q(t_0,t)$, $\Delta\bar{q}(t_0)$, and $\Delta q(t_0,T)$ represent the increase in the component unavailability due to test-caused degradation and aging effects.

Pictorial Representation of Time-dependent Component Unavailability

Figure 6.1 shows the schematic of time-dependent unavailability, $q(t)$, of a periodically-tested component, for two different cases. When neither test-caused degradation effect nor long-term aging effect is taken into account, the unavailability will vary with time as shown in Figure 6.1-a. Figure 6.1-b represents the case where either or both of the two effects is taken into consideration in evaluating $q(t)$. As shown in this figure, $q(t)$ will increase globally over time in this case because of the accumulation of the test-caused degradation and/or aging effects on the component.

Unavailability Doubling Time Considerations

The unavailability of a periodically tested component will increase globally over time as more tests are performed on the component and as the time passes by (see Figure 6.1-b). This global increase in the component unavailability can be represented by defining a component unavailability doubling time.

Let

t_D = the component unavailability doubling time at which the initial component unavailability is doubled, (6.36)

and

n_D = the number of tests associated with the component unavailability doubling time. (6.37)

Then, we have the following relationship between t_D and n_D:

$$t_D = n_D T \tag{6.38}$$

The number of tests associated with the doubling time, n_D, can then be obtained by setting the average unavailability increase after n_D tests, i.e., $\Delta\bar{q}(n_D)$, equal to the initial average unavailability, i.e., $\bar{q}$:

$$\Delta\bar{q}(n_D) = \bar{q} \tag{6.39}$$

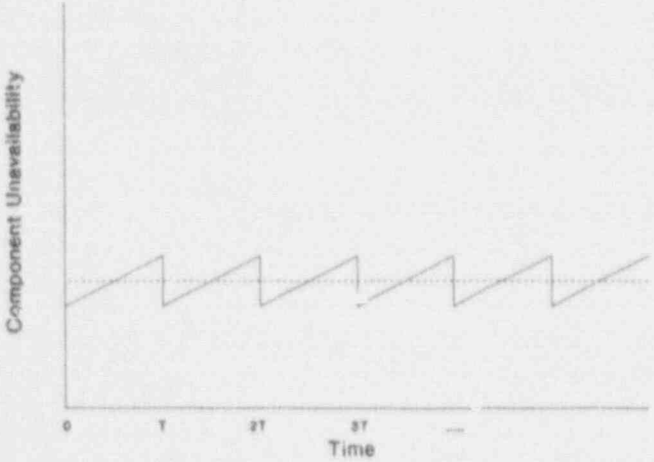
Solving Equation (6.39) by use of Equations (6.14) and (6.34), we have the following expression for the number of tests associated with the doubling time:

$$n_D = \frac{\rho_0 + \frac{1}{2}\lambda_0 T}{\rho_0 P_1 + \frac{1}{2}\lambda_0 P_2 T} \tag{6.40}$$

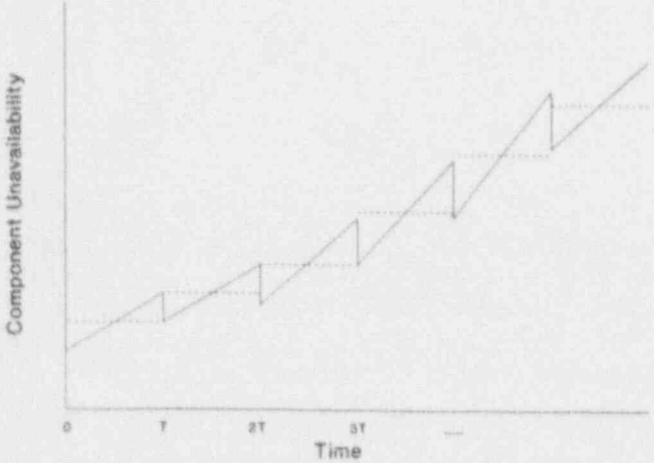
where only the test-caused degradation effect is taken into account without considering the aging effect, i.e., $\alpha = 0$.

Therefore, the component unavailability doubling time can be estimated by:

$$t_D = \frac{(\rho_0 + \frac{1}{2}\lambda_0 T)T}{\rho_0 P_1 + \frac{1}{2}\lambda_0 P_2 T} \tag{6.41}$$



a) Without Test-Caused Degradation and Aging Effects



b) With Test-Caused Degradation and Aging Effects

Figure 6.1. Time-dependent component unavailability, q(t), versus test-caused degradation and aging effects
(T is the test interval of the component, and horizontal dotted lines indicate average component unavailabilities.)

Component Renewal Considerations

When a component is found to be in a serious degradation or failure condition, it will be replaced or effectively restored to as good as new condition. This subsection presents how the component renewal or overhaul can be taken into account in the component degradation model.

The average unavailability change at t_0, $\Delta\bar{q}(t_0)$, can be assessed by averaging the time-dependent unavailability change, $\Delta q(t_0,t)$, between t_0 and $t_0 + T$:

$$\Delta\bar{q}(t_0) = \frac{1}{T}\int_0^T \Delta q(t_0,t')dt' \qquad (6.42)$$

where t_0 is measured from the last renewal point.

Inserting the expression for $\Delta q(t_0,t)$ given by Equation (6.33) into Equation (6.42) yields:

$$\Delta\bar{q}(t_0) = p_1\rho_0\frac{t_0}{T} + \frac{1}{2}p_2\lambda_0 t_0 + \frac{\alpha}{2}(t_0 T + \frac{T^2}{3}) \qquad (6.43)$$

which is equivalent to Equation (6.34).

The average component unavailability, $\Delta\bar{\bar{q}}$, during the renewal interval, L, can then be obtained by treating t_0 as a continuous variable and averaging $\Delta\bar{q}(t_0)$ between 0 and L-T:

$$\Delta\bar{\bar{q}} = \frac{1}{L-T}\int_0^{L-T} \Delta\bar{q}(t_0)dt_0 = \frac{\rho_0 p_1}{2}\,\frac{L-T}{T} + \frac{\lambda_0 p_2}{4}(L-T) + \frac{\alpha}{4}T(L-T) + \frac{\alpha}{6}T^2 \qquad (6.44)$$

In Equation (6.44), L-T is used instead of L because the last surveillance test is at L-T; however, it does not make much difference since, in general, L is far larger than T.

In actual practice, L may vary. In this case, the L can be taken as the average value. If there are inefficiencies associated with the renewal, the effective overhaul interval can be used as discussed in Reference 17.

6.2 Formulas for the Risk Impacts of Component Degradations

6.2.1 Risk Benefit of a Surveillance Test

As discussed earlier in the report, the risk benefit of surveillance testing results from the detection of component failures or degradation conditions. The formula for the risk benefit of tests is presented here again in terms of the parameters explored in the previous section.

Let

$\bar{R}_D$ = the average risk benefit or test-detected risk contribution of a surveillance test (6.45)

and

$\bar{q}(T)$ = the average probability that the component is found to be in a down state when the test is conducted at $t = T$. (6.46)

The average risk benefit of a test, $\bar{R}_D$, can then be represented as:

$$\bar{R}_D = \bar{q}(T)\,[R_1 - R_0]$$

$$= \frac{\lambda_0 T}{2}\,[R_1 - R_0] \tag{6.47}$$

where R_0 is the core damage frequency evaluated with the component assumed up, and R_1 is the core damage frequency with the component assumed down.

6.2.2 Risk Penalty of a Surveillance Test Due to Test-Caused Equipment Wear

The risk penalty of a test, i.e., test-caused risk contribution, due to equipment wear can be evaluated, taking into account the unavailability of the component before and after the test, along with the risk impacts evaluated assuming the component is up or down.

According to Equation (6.34), the average increase in component unavailability that results from n tests is:

$$\Delta\bar{q}(t_0) \equiv \Delta\overline{q_n}$$

$$= p_1\rho_0 n + \frac{1}{2}p_2\lambda_0 T n \tag{6.48}$$

where only the test-caused degradation effect is taken into account without considering the aging effect, i.e., $\alpha = 0$.

We can now define the average test-caused risk contribution which explicitly incorporates the number of tests:

$\bar{R}_{C,n}$ = the average risk increase or test-caused risk contribution resulting from test-caused degradations of n tests performed on the equipment (6.49)

In a similar manner as the average risk benefit of a test was obtained, the formula for $\bar{R}_{C,n}$ can then be derived as follows:

$$\bar{R}_{C,n} = \text{the average risk level between } [t_0, t_0 + T] - \text{the average risk level between } [0,T]$$

$$= \left[\{1 - \bar{q} - \Delta\bar{q}(t_0)\} R_0 + \{\bar{q} + \Delta\bar{q}(t_0)\} R_1\right] - \left\{(1 - \bar{q}) R_0 + \bar{q} R_1\right\}$$

$$= \Delta\overline{\bar{q}_n}\, [R_1 - R_0] \tag{6.50}$$

In Equation (6.50), R_1 is the core damage frequency evaluated with the component assumed down, i.e., unavailability of unity, and R_0 is the core damage frequency evaluated with the component assumed up, i.e., unavailability of zero as previously described.

Thus, we have arrived at the average core damage frequency contribution caused by the test, $\bar{R}_{C,n}$, as a function of the number of tests performed on the component since the last overhaul. The expression for the test-caused risk contribution, given in Equation (6.50), takes into account the accumulated degradation effects on the equipment by a multitude of tests.

6.2.3 Renewal Considerations

The overall, average test-caused risk contribution, $\bar{R}_{C,n}$, due to equipment degradations during a renewal time period can be represented as:

$$\overline{\overline{R}}_{C,n} = \Delta\overline{\overline{q}}[R_1 - R_0] \tag{6.51}$$

where $\Delta\overline{\overline{q}}$ is given in Equation (6.44).

6.2.4 Risk Effectiveness of Surveillance Testing with Regard to Test-Caused Degradation

Based on the formulas developed heretofore, we can now evaluate the risk effectiveness of a test with regard to test-caused component degradation. For the test to be risk-effective, the risk contribution detected by the test should be larger than the risk contribution caused by the test:

$$\bar{R}_D > \bar{R}_{C,n} : \text{ n-th test risk-effective with regard to test-caused degradation} \tag{6.52}$$

Substituting the expressions for $\bar{R}_D$ and $\bar{R}_{C,n}$ given by Equations (6.47) and (6.50) and simplifying, we arrive at the following criterion on the number of tests:

$$n < \frac{\frac{1}{2}\lambda_0 T}{\rho_0 P_1 + \frac{1}{2}\lambda_0 P_2 T} : \quad \text{n-th test risk-effective with regard to test-caused degradation} \tag{6.53}$$

Thus, for the n-th test to be risk-effective with regard to test-caused degradation, the number of tests performed on the component since the last overhaul should satisfy the above criterion. When the number of tests on the component is less than the value of the right-hand side in the criterion, then the core damage frequency contribution caused by the test will be less than the core damage frequency contribution detected by the test; and vice versa.

6.3 Assumptions and Limitations of the Model

The test-caused component degradation model is a comprehensive model that not only incorporates aging effects, but separately takes into account test-caused degradation effects as well. However, the degradation model and the formulas for evaluating the risk impact associated with test-caused degradations are based on the following assumptions that may shed light on some limitations in the use of the approaches:

(1) Test-caused component degradations impact not only demand failure probability, but also standby failure rate; i.e., the component will be more vulnerable to both demand and standby time-related failures as more tests are performed on the component.

(2) The standby time-related failure rate increases due to not only test-caused degradation effects, but also aging effects. However, the aging does not affect the probability that the component will fail upon demand, i.e., the demand failure probability.

(3) The time-dependent aging mechanism on the standby failure rate can be represented by a Weibull distribution.

(4) The demand degradation or failure mechanism is not affected by the time. In other words, the demand failure probability depends on only the number of tests performed on the equipment, but not on the idle or dormant time.

(5) The test impact parameters, β_1 and β_2, and the aging impact parameter, β_3, cannot be easily estimated using typically available data on component degradations or failures. Therefore, in most cases it may be necessary to use a linear model for some or all of those parameters.

6.4 Sensitivity Analyses

Based on the component degradation model and formulas for evaluating the risk impact of test-caused degradations presented heretofore, sensitivity analyses were carried out on test-caused degradation effects. The diesel generator was chosen as the sample component in this study because it was identified as suffering from test-caused degradation effects by engineering analyses.[1] However, the method presented here can also be applied to any other component.

The component degradation model contains a number of parameters that should be estimated to evaluate the risk impact and perform the sensitivity analyses. In this subsection, the formulas for estimating the degradation parameters are first developed. These formulas are generic; they can be used for any kind of component. The parameter values for diesel generators are then obtained using the formulas. The results of sensitivity studies for diesels will finally be presented.

6.4.1 Formulas for Estimating Degradation Parameters

The parameters used in the test-caused component degradation model presented earlier, i.e., ρ_0, λ_0, p_1, p_2, and α, cannot be easily estimated from the actual data base, because the data base, generally, does not provide such detailed information. However, among the parameters, the residuals, ρ_0 and λ_0, can be roughly estimated from the data base as:

$$\rho_0 = \frac{\text{Number of demand-related failures}}{\text{Total number of demands}} \tag{6.54}$$

$$\lambda_0 = \frac{\text{Number of standby time-related failures}}{\text{Total standby time}} \tag{6.55}$$

The other three parameters, p_1, p_2, and α, can be estimated first deriving formulas for the maximum values, i.e., p_{1m}, p_{2m}, and α_m, under the assumption that:

> When the number of tests is large, the average increase in component unavailability which is evaluated by the test-caused component degradation model presented in the report is the same as that estimated by the aging model.[17]

The maximum parameter values can then be represented in terms of other known parameters as follows:

$$p_{1m} = \frac{aT^2}{2\rho_0} \tag{6.56}$$

$$p_{2m} = \frac{aT}{\lambda_0} \tag{6.57}$$

$$\alpha_m = a \tag{6.58}$$

where a is the linear aging rate of the aging model. These formulas, i.e., Equations (6.56) to (6.58), are derived in Appendix B.

6.4.2 Evaluation of Degradation Parameters for Diesel Generators

A number of reliability studies have been performed on diesel generators because of the great importance of diesel reliability in nuclear plant safety and the implication of adverse risk impacts due to the frequent testing and ensuing equipment degradations. Table 6.1 shows some degradation parameters, and their values for diesel generators that were taken from the results of previous studies on diesel generator reliability.[16-18]

The values of these degradation parameters, in fact, depend on the specific diesel generator. Particularly, the ratio for demand-related failures to standby time-related failures, n_1:n_2, is strongly component-specific. Therefore, whenever possible, the parameter values should be obtained for the specific diesel generator, for which the test risk-effectiveness evaluation is to be performed. In this study, the values presented in Table 6.1 will be used to perform the sensitivity analysis and illustrate the risk-effectiveness evaluation of the test.

Table 6.1. Degradation Parameters for Diesel Generators[16-18]

Degradation Parameter	Value
Residual demand failure probability, ρ_0 (per demand)	2E-2
Residual standby time-related failure rate, λ_0 (per hour)	2E-5
Linear aging rate, a (per hour per year)	4E-6
Ratio of demand-related failures to standby time-related failures, n_1:n_2	2:1

The maximum test degradation parameters, p_{1m} and p_{2m}, which were discussed in the previous section, can be estimated using the parameter values in Table 6.1: p_{1m} = 5.9E-3 and p_{2m} = 1.6E-2. From these maximum values, p_{1m} and p_{2m}, and the ratio of demand-related failures to standby time-related failures in Table 6.1, i.e., 2:1, the values of the test degradation parameters, p_1 and p_2, for diesel generators can then be estimated as:

$$p_1 = p_{1m} \frac{n_1}{n_1 + n_2} = 3.9 \text{ E-3}$$

$$p_2 = p_{2m} \frac{n_2}{n_1 + n_2} = 5.5 \text{ E-3}$$

Sensitivity studies on test-caused degradations of diesel generators were performed using the parameter values obtained in this section. The results of the studies are presented in the following section.

6.4.3 Results of Sensitivity Studies for Test-Caused Degradations of Diesel Generators

Figures 6.2 to 6.4 show the sensitivity of component unavailability to the number of tests, the test frequency, and the relative degradation mechanism, i.e., demand-related degradations versus standby time-related degradations. The unavailability actually plotted in the figures is the ratio of the unavailability increase to the initial unavailability, that is:

$$\delta q_n = \frac{\Delta q_n}{\bar{q}} \tag{6.59}$$

The test frequencies considered are 4, 12, and 120 times a year; the corresponding test intervals are 3 months, 1 month, and 3 days, respectively. Technical specifications typically require monthly testing of diesel generators, but more frequent testing is required based on the number of failures observed in the last 100 tests.[19]

The cyclic, i.e., demand-related degradation mechanism is assumed to be predominant over the standby time-related degradation mechanism in Figure 6.2. On the other hand, Figure 6.3 assumes the predominance of standby time-related degradation. Figure 6.4 shows the sensitivity of the diesel generator unavailability to changes in the number of tests and the test frequency, with 2:1 as the ratio of the effect of cyclic to standby time-related degradation. Also shown in the figures are unavailability doubling times, t_D, which were discussed in Section 6.1.

We can note by comparing Figure 6.2 with Figure 6.3 that, in general:

(1) When the demand-related degradation is predominant, the larger the test interval, the component unavailability becomes smaller.

(2) When the standby time-related degradation is predominant, the smaller the test interval, the component unavailability becomes smaller.

Figures 6.5 and 6.6 show the sensitivity of the average test-caused risk due to equipment wear to the changes in degradation effect and test frequency, where the overhaul time of the diesel generator is assumed to be 2 and 6 years, respectively. The test-caused risk is the most sensitive to the variation in the test frequency when the cyclic degradation effect is predominant. However, when the standby time-related degradation effect is predominantit is almost insensitive to the change in test frequency. A similar trend of sensitivity is obtained in both cases; however, the overall test-caused risk is higher for longer overhaul time.

Important results of risk-effectiveness evaluation for the diesel generators, which have such degradation and failure characteristics as specified in Table 6.1, are presented in Figures 6.7 and 6.8. These figures show the variation of the following three different kinds of risk impacts to the number of tests: (1) the test-detected risk contribution, $\bar{R}_D$, (2) the test-caused risk contribution due to test-caused equipment wear, $\bar{R}_{C,n}$, and (3) the total risk impact of the test, $\bar{R}_{T,n}$.

Figure 6.7 is for monthly testing of the diesel generators, while Figure 6.8 is for quarterly testing. In the case of monthly testing, the test is risk-effective until 61 tests have been performed, i.e., approximately 5 years after the last overhaul point. In the case of quarterly testing, the test is risk-effective until 111 tests have been performed, i.e., about 28 years. However, at the time after which the test becomes no longer risk-effective, the total risk impact for quarterly testing (1.1E-4 per year) is greater than that for monthly testing (3.5E-5 per year) by approximately a factor of 3.1, as can be seen by comparing the two figures.

Figure 6.9 shows the risk-effective lifetime for diesel generator testing, i.e., the time period during which the tests performed on the diesel generators remain risk-effective, and the total risk at the end of the lifetime as a function of test interval. The lifetime increases with increasing test interval, because of a slower accumulation of test-caused degradation effects on the equipment. However, the total risk at the end of the lifetime also increases when the test interval is increased. For example, if the test interval of 1 month is extended to 3 months, then the risk-effective lifetime will increase from 5 years to 28 years, i.e., by a factor of 5.6. However, the total risk at the end of the lifetime for quarterly testing will be higher by a factor of 3.1 than that for monthly testing as was discussed above.

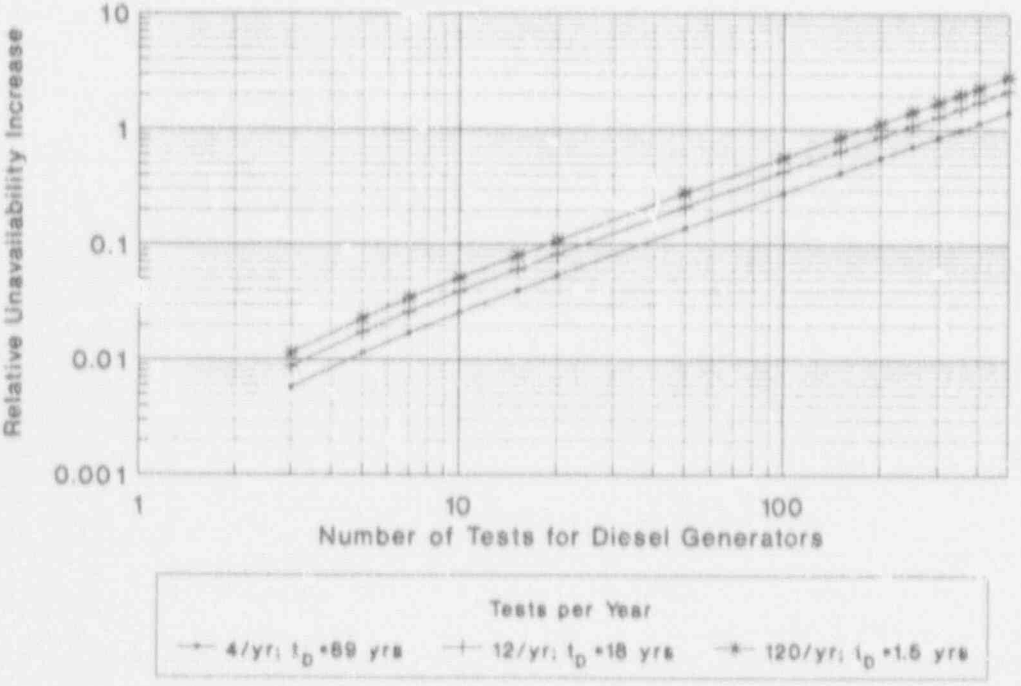


Figure 6.2. Sensitivity of the relative unavailability increase, δq_{n}, of the diesel generator to the number of tests and the test frequency when the cyclic effect is predominant (t_D is the unavailability doubling time.)

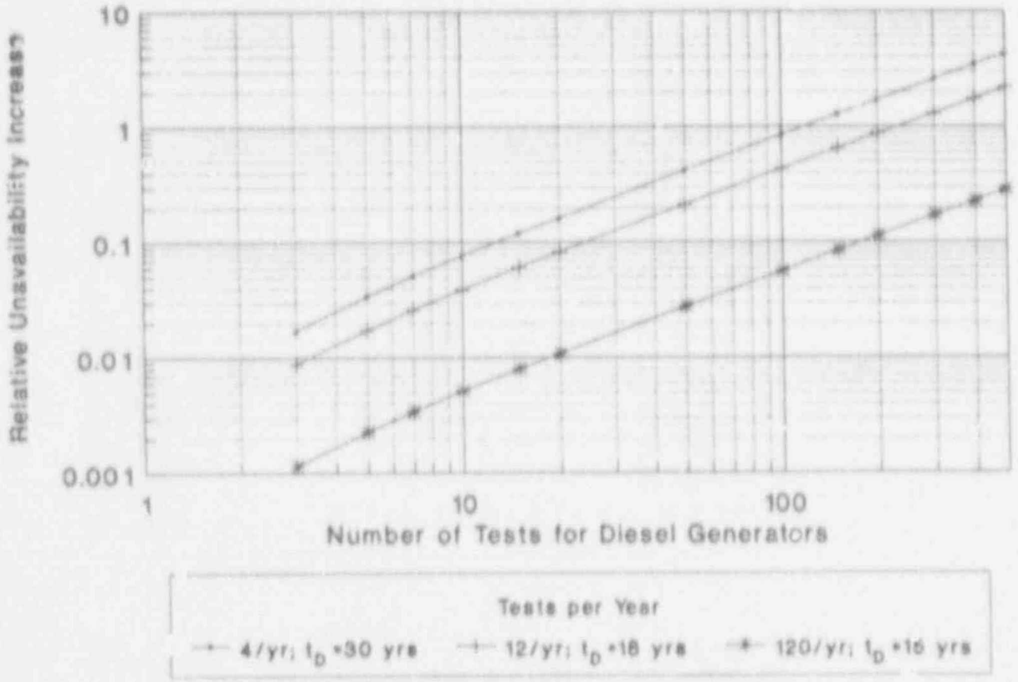


Figure 6.3. Sensitivity of the relative unavailability increase, δq_a, of the diesel generator to the number of tests and the test frequency when the standby effect is predominant (t_D is the unavailability doubling time.)

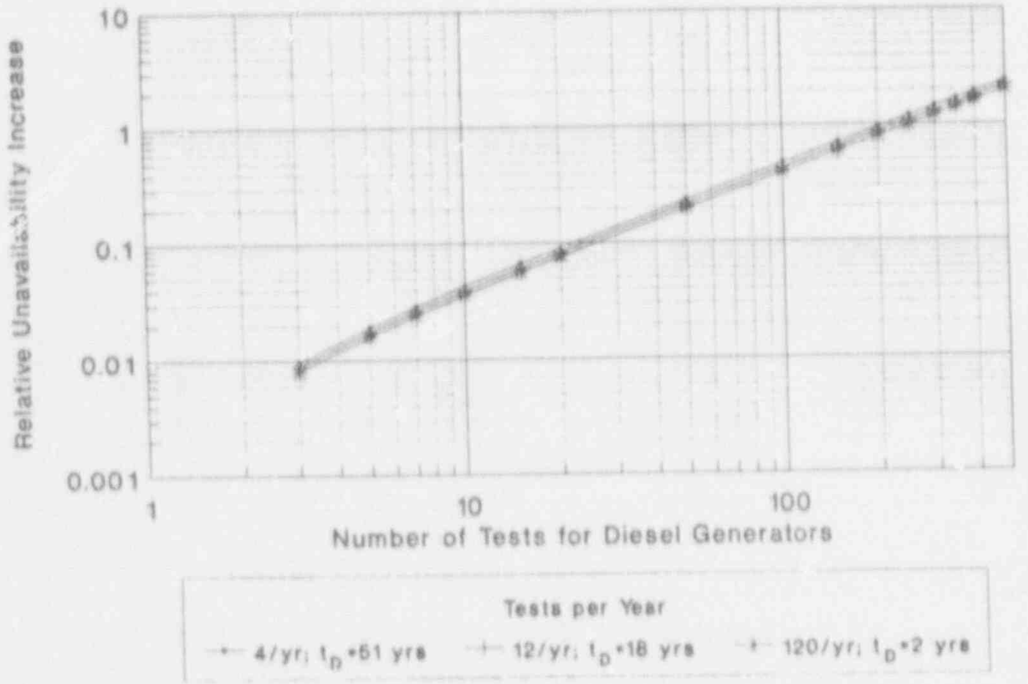


Figure 6.4. Sensitivity of the relative unavailability increase, δq_a, of the diesel generator to the number of tests and the test frequency when the cyclic and standby effects are 2:1 (t_D is the unavailability doubling time.)

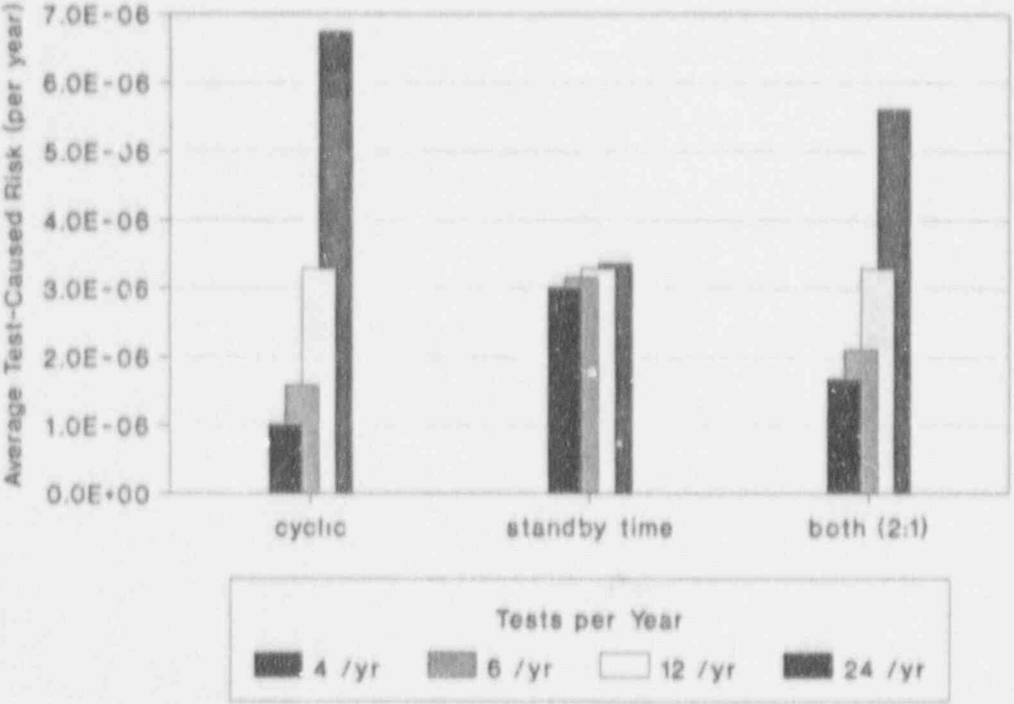


Figure 6.5. Sensitivity of the average test-caused risk due to equipment wear to the variations in degradation effects and test frequency when the overhaul time is 2 year

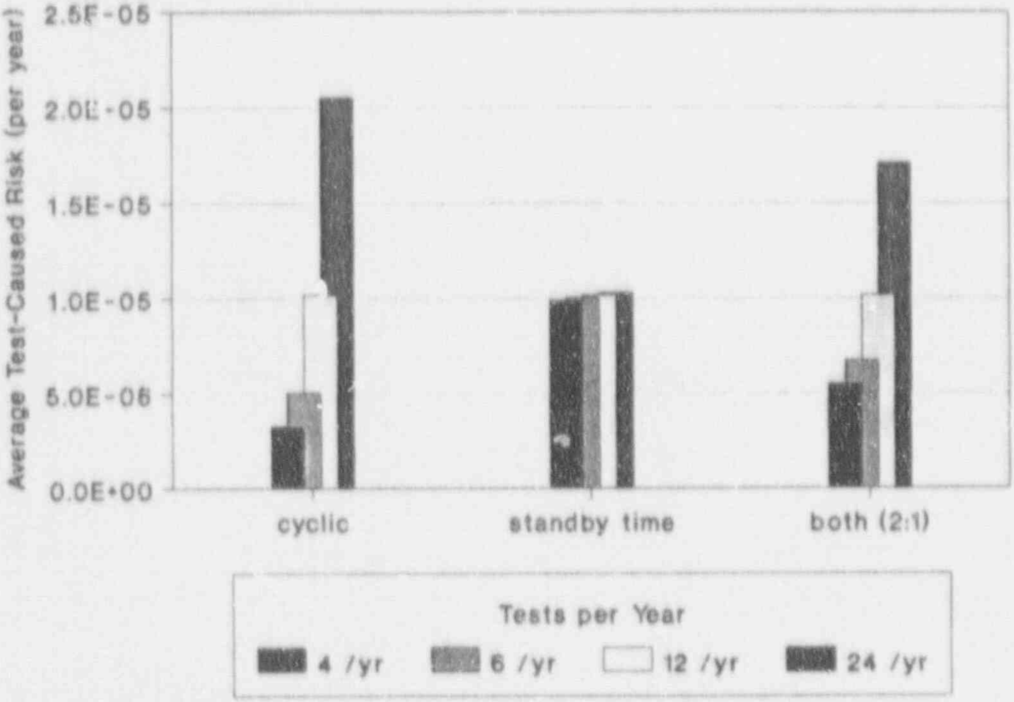


Figure 6.6. Sensitivity of the average test-caused risk due to the equipment wear to the variations in degradation effects and test frequency when the overhaul time is 6 years

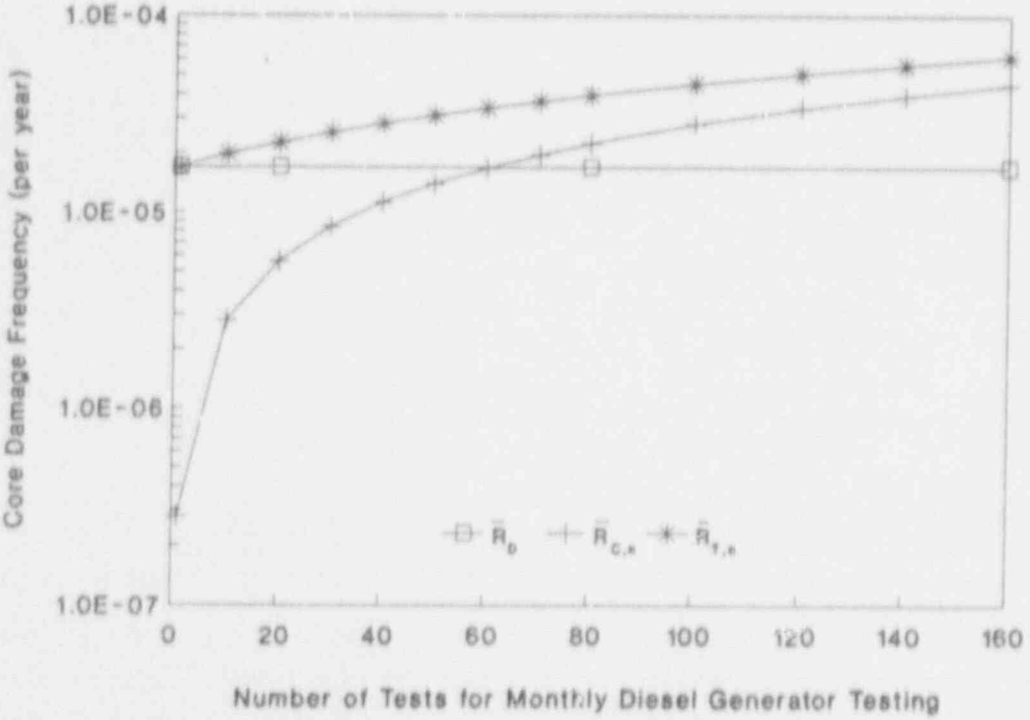


Figure 6.7. Evaluation of risk-effectiveness for monthly diesel generator testing ($\bar{R}_D$ = test-detected risk impact; $\bar{R}_{C,n}$ = test-caused risk impact due to equipment wear; $\bar{R}_{T,n}$ = total risk impact of the test)

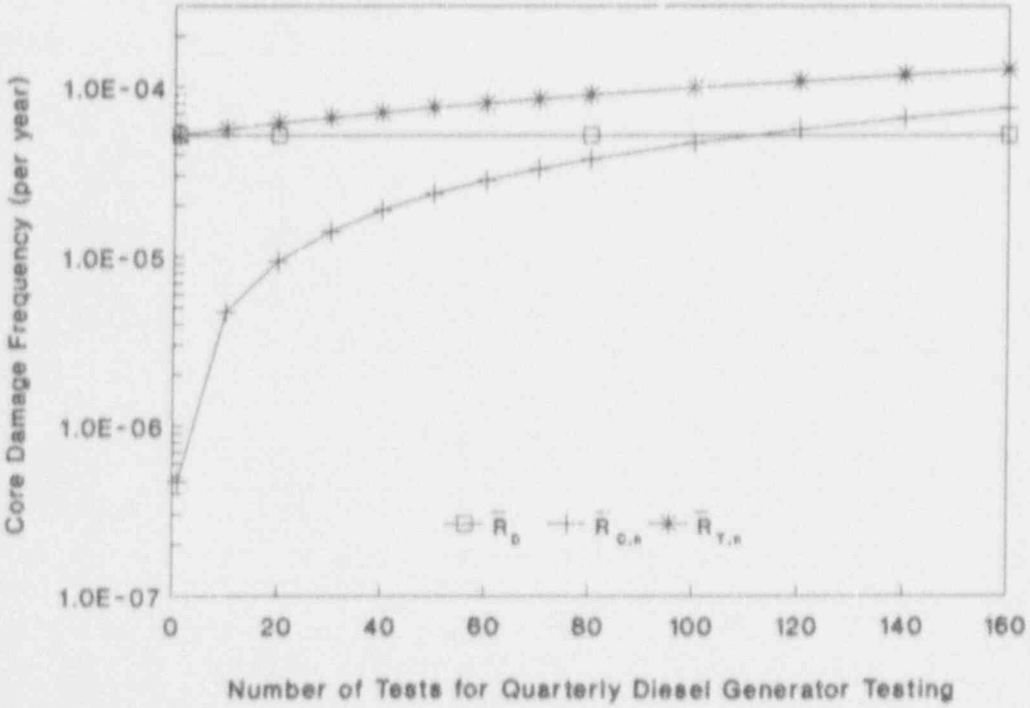


Figure 6.8. Evaluation of risk-effectiveness for quarterly diesel generator testing ($\bar{R}_D$ = test-detected risk impact; $\bar{R}_{C,n}$ = test-caused risk impact due to equipment wear; $\bar{R}_{T,n}$ = total risk impact of the test)

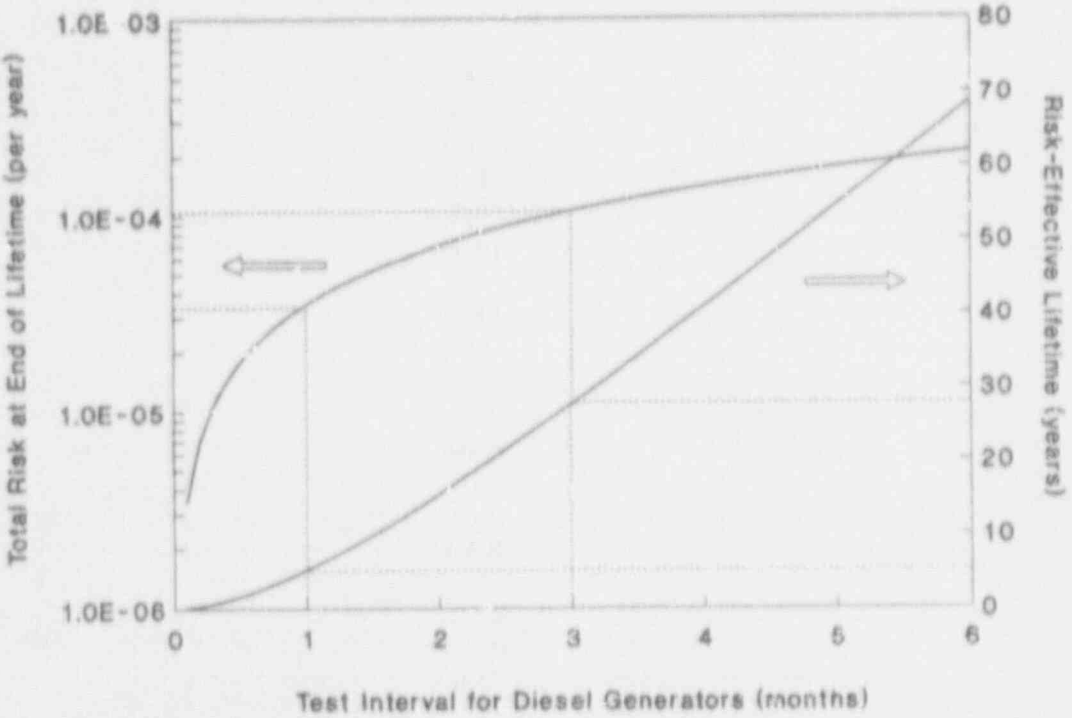


Figure 6.9. Evaluation of risk-effective lifetime and the total test risk at the end of lifetime versus test interval of diesel generators (Dotted lines indicate the lifetime and the total risk for monthly and quarterly testing.)

7. SUMMARY AND CONCLUSIONS

In this report, the basic concepts for the risk-effectiveness evaluation of surveillance test requirements are presented along with a risk perspective of the various adverse risk effects of testing. The formulas for the beneficial risk impact of testing, i.e., "test-detected" risk impact, are briefly summarized.[4] The major thrust of this report is the presentation of the methodology to evaluate the adverse risk impact, i.e., "test-caused" risk impact, focusing on two important kinds: 1) risk impact of plant transients which occur due to testing and 2) risk impact of equipment wear-out which is caused by tests.

The fundamental notion and characteristics of the methodology for the test-caused risk impact due to transients are as follows:

(1) The test-caused transients, which cause or require a reactor scram, are initiating events. The risk impacts of these initiators are assessed in PRAs which model the functions of the various safety systems and the operator actions following the initiators. Therefore, the risk impact associated with the test-caused transients can be evaluated through the risk impact of initiating events of a PRA model.

(2) To estimate the risk impact of the test-caused transients from the risk impact of initiating events, it is necessary to identify the extent to which the frequency of the initiating event group is attributable to the test-caused transients. This identification can be done by analyzing plant operating data.

(3) In this methodology, the probability that a transient will occur during a test can be estimated by analyzing operating data in the framework of a PRA model. Once a reasonable estimate of the probability is established from the data, the adverse risk impact due to test-caused transients can be evaluated as a function of the test interval along with the beneficial risk impact of the test for risk-effectiveness evaluation.

The methodology for evaluating the risk impact associated with equipment wear due to surveillance testing is based on the test-caused component degradation model which was developed, in this study, from the concept of stress on the component. The model satisfies the following requirements for modeling the progressive component degradations due to testing:

(1) Standby components that are tested on a periodic basis become degraded over time due to two different kinds of stresses: demand stress from surveillance tests (or actual operating requirements), and standby stress from the environmental or aging effect. Hence, the model should account for both stresses.

(2) The model should also explicitly incorporate the number of tests, because the equipment degradation depends on how many tests have been performed on the equipment since the last overhaul time.

The methodology for evaluating the test-caused risk contributions due to test-caused transients and test-caused equipment degradations was applied to a selected set of tests. For the test-caused transients, four tests were selected: 1) MSIV operability test, 2) turbine overspeed protection system test, 3) control rod movement test, and 4) ESFAS slave relay test. For the test-caused equipment degradations, the emergency diesel generator was chosen as the sample component because of the concern of the test-caused degradations on this component and the availability of the reliability data that are necessary for estimating the degradation parameters of the model.

The risk-effectiveness evaluation has been carried out for the MSIV operability test and the diesel generator test. Based on the numerical results from the data analysis conducted in this study, the quarterly MSIV operability test is risk-effective with regard to test-caused transients because the test interval is greater than the minimum test interval of 54 days for the risk-effective test. The data analysis indicates that some plants test MSIVs more frequently than 54 days. For those plants, the MSIV operability test would be risk-ineffective with regard to test-caused transients, if the assumptions of the analysis were still valid for those. Detailed plant-specific evaluations considering the specific MSIV testing are recommended before modifying the test frequency.

The risk-effectiveness of the diesel generator test was evaluated for two different test intervals, i.e., 3 months and 1 month. When the diesel generator is tested quarterly, the test-caused component degradation model indicates that the surveillance test is risk-effective until 111 tests have been conducted, i.e., approximately 28 years after the last overhaul point. However, in the case of monthly testing, the model indicates that the test becomes risk-ineffective after 61 tests have been conducted, i.e., about 5 years. These evaluations were carried out using the parameter values that were estimated from the results of the various diesel-generator reliability studies. Hence, to obtain more meaningful results that are applicable to specific components, the values of the degradation parameters should be estimated for the specific diesel generators and used in the model to assess the test-caused risk contribution.

In conclusion, the safety significance or risk-effectiveness of surveillance test requirements can be evaluated with explicit consideration of the adverse effects of testing, based on the concepts and methods provided in this report. The quantitative risk evaluation results can be used in the decision making process for the establishment of the safety significance of the surveillance testing and for the screening of the surveillance requirements. These results should be used in conjunction with the qualitative evaluation results[1] from engineering considerations and operating experience, such as qualitative evaluations with respect to radiation exposure to plant personnel from the tests and test-caused operator burden. These evaluations can be useful to both the regulatory body and the nuclear power plant licensees.

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APPENDIX A

DESCRIPTIONS OF TEST-CAUSED TRANSIENT EVENTS

This section presents the descriptions of the test-caused transient events that were identified from the data analysis performed in this study. Tables A.1 and A.2 describe the transient events which occurred during turbine overspeed protection system testing and MSIV operability testing, respectively.

Table A.1. Descriptions of Transient Events that Occurred During Turbine Overspeed Protection System Testing

Plant	LER and Event Date	Description of Event	Root Cause
Dresden 3	85-001/ 011285	The reactor scrammed from a turbine trip due to a malfunction of the oil trip solenoid valve which stuck open leading to the induction of an overspeed trip signal. The solenoid valve was stuck due to grease contamination of the button guide.	Equipment failure
Quad Cities 2	85-001/ 012585	During operability test of the 4 turbine control valves, control valve #4 immediately fast closed. The resulting pressure spike caused high neutron flux, which then resulted in reactor trip by the RPS.	Equipment failure
Susquehanna 2	85-003/ 011985	During the performance of the test, the #1 control valve was closed with high vibration on the #1 and #2 bearings. The main turbine tripped on the high vibration.	Equipment failure
Fitzpatrick	85-021/ 072685 080985	Two reactor scrams occurred due to the operator not holding the test pushbutton long enough to allow valves to reposition properly. The post-investigation through testing of the electrohydraulic control (EHC) system, using a simulator, revealed large pressure transients on the emergency trip supply (ETS) fluid upon the release of the test pushbutton. Orifices were installed on the ETS lines for all valves which have zero leakage shut-off valves to reduce the pressure transient when performing valve testing.	Operator error
Peach Bottom 2	85-011/ 080585	A full scram occurred due to reactor water level transient during turbine control valve surveillance testing. The transient was caused by a momentary decrease in oil pressure of the relayed emergency trip system (RETS), in conjunction with the setpoint drift of the pressure switch that monitors oil pressure at the RETS supply to the No. 4 main turbine control valve.	Equipment failure

Table A.2. Descriptions of Transient Events that Occurred During MSIV Operability Testing

Plant	LER and Event Date	Description of Event	Root Cause
Quad Cities 2	85-005/ 021985	While performing the biweekly MSIV operability surveillance, the 203-2B outboard MSIV went to the fully closed position instead of stopping at the 10% closure limit due to a failed limit switch on the MSIV.	Equipment failure
Hatch 2	85-001/ 011985	During performance of the MSIV trip test procedure, the 'A' inboard MSIV failed to operate within the time limits of tech specs. Plant personnel then cycled the MSIV repeatedly to see if its time would change. During this cycling, the MSIV drifted to less then 90% open, resulting in an unplanned scram. The investigation determined that the continuous cyclings of the MSIV resulted in a high rate of charging flow to the MSIVs accumulator.	Procedure inadequacy
Brunswick 2	85-011/ 101585	During the performance of the periodic test, MSIV B21-F022A auto-closed. Reactor pressure spiked and the unit auto-scrammed on high power. When the AC solenoid on the 3-way solenoid valve of the MSIV was deenergized, the MSIV closed because the corresponding DC solenoid Rad unknowingly failed at a prior indeterminate time.	Equipment failure

APPENDIX B

DERIVATION OF FORMULAS FOR MAXIMUM TEST-CAUSED DEGRADATION AND AGING PARAMETERS

This appendix derives the formulas for maximum test-caused degradation and aging parameters, i.e., p_{1m}, p_{2m}, and α_m, which were presented in Equations (6.56) to (6.58) of Section 6. The component degradation model presented in the section takes into account both test-caused degradation and aging effects. The average increase in component unavailability due to these effects, $\Delta\overline{q}_1(t_0)$, after n tests were performed on the component, can be expressed from Equation (6.34) as follows:

$$\Delta\overline{q_1}(t_0) = p_1\rho_0\frac{t_0}{T} + \frac{1}{2}p_2\lambda_0 t_0 + \frac{\alpha}{2}(t_0 T + \frac{T^2}{3}) \qquad \text{(B.1)}$$

where $t_0 = nT$ and T is the test interval.

On the other hand, the linear aging model[15] assumes that the increase in component unavailability is only due to aging effects, without taking into account the test-caused degradation effect. Under this assumption, we obtain the following expression for the average increase in component unavailability, $\Delta\overline{q}_2(t_0)$, by setting $\alpha = a$, $p_1 = 0$, and $p_2 = 0$ in Equation (B.1):

$$\Delta\overline{q_2}(t_0) = \frac{a}{2}(t_0 T + \frac{T^2}{3}) \qquad \text{(B.2)}$$

where a is the linear aging rate evaluated in the aging model. The value for the parameter, a, was derived for several components.

Let $t_{0i} = it_0$, where $0 \le i \le n$. Equations (B.1) and (B.2) can then be re-expressed as follows:

$$\Delta\overline{q_1}(t_{0i}) = p_1\rho_{0i} + \frac{1}{2}p_2\lambda_0 iT + \frac{\alpha}{2}(iT^2 + \frac{T^2}{3}) \qquad \text{(B.3)}$$

$$\Delta\overline{q_2}(t_{0i}) = \frac{a}{2}(iT^2 + \frac{T^2}{3}) \qquad \text{(B.4)}$$

We can now obtain the following expressions for the average increase in unavailability over n tests:

$$\Delta\overline{\overline{q}}_1 = \frac{1}{n}\sum_{i=1}^{n} \Delta\overline{q_1}(t_{0i}) \qquad \text{(B.5)}$$

$$\Delta\overline{\overline{q}}_2 = \frac{1}{n}\sum_{i=1}^{n} \Delta\overline{q_2}(t_{0i}) \tag{B.6}$$

where $\Delta\overline{\overline{q}}_1$ and $\Delta\overline{\overline{q}}_2$ denote the average unavailability increase based on the component degradation model and the aging model, respectively.

Substituting the expressions for $\Delta\overline{q_1}(t_{0i})$ and $\Delta\overline{q_2}(t_{0i})$ into Equations (B.5) and (B.6), we have the following expressions:

$$\Delta\overline{\overline{q}}_1 = p_1\rho_0\frac{n+1}{2} + p_2\lambda_0 T\frac{n+1}{4} + \frac{\alpha T^2}{2}\left\{\frac{1}{3} + \frac{n+1}{2}\right\} \tag{B.7}$$

$$\Delta\overline{\overline{q}}_2 = \frac{aT^2}{2}\left\{\frac{1}{3} + \frac{n+1}{2}\right\} \tag{B.8}$$

Assume that when the number of tests is large, the average increase in the component unavailability evaluated by the component degradation model is the same as that estimated by the aging model. From Equations (B.7) and (B.8), we then obtain the following expression:

$$a = \frac{2p_1\rho_0}{T^2} + \frac{p_2\lambda_0}{T} + \alpha \tag{B.9}$$

From Equation (B.9), we can obtain the following formula for the maximum test degradation factor associated with demand-related failures, i.e., p_{1m}, by setting the second and third terms in the right-hand side equal to zero:

$$p_{1m} = \frac{aT^2}{2\rho_0} \tag{B.10}$$

Similarly, we also can derive the following formulas for the maximum test degradation factor associated with standby time-related failures, i.e., p_{2m}, and the maximum aging parameter, i.e., α_m:

$$p_{2m} = \frac{aT}{\lambda_0} \tag{B.11}$$

$$\alpha_m = a \tag{B.12}$$

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Concerns have been raised regarding the adverse safety impact of surveillance testing and generally overburdensome surveillance requirements. To evaluate these concerns, the risk-effectiveness of surveillance tests has been studied with explicit consideration of the negative risk impact, in conjunction with the positive risk impact. This report defines the negative effects of surveillance testing from a risk perspective, and then presents the methodology by which the negative risk impact can be quantified, focusing on two important kinds of negative risk impact of surveillance testing: (1) risk impact of test-caused trips and (2) risk impact of test-caused equipment wear.

Using the methodology presented, these negative risk impacts are evaluated for a selected set of surveillance tests for demonstration examples. The results of the risk-effectiveness evaluation are provided along with the insights from the sensitivity analyses.

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