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Evaluations and Utilizations of Risk Importances

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Battelle's Columbus Laboratories

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U.S. Nuclear Regulatory Commission

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EXECUTIVE SUMMARY

This report presents approaches for utilizing Probabilistic Risk Analyses (PRA's) to determine risk importances. Risk importances are determined for design features, plant operations, and other factors that can affect risk. PRA's can be used to identify the importances of risk contributors or proposed changes to designs or operations. The objective of this report is to serve as a handbook and guide in evaluating and applying risk importances.

The utilization of both qualitative risk importances and quantitative risk importances is described in this report. Qualitative risk importances are based on the logic models in the PRA, while quantitative risk importances are based on the quantitative results of the PRA. Both types of importances are among the most robust and meaningful information a PRA can provide.

A wide variety of risk importance evaluations are described including evaluations of the importances of design changes, testing, maintenance, degrading environments, and aging. Specific utilizations are described in inspection and in reliability assurance programs, however the general approaches have widespread applicability. The role of personal computers and decision support programs in applying risk importance evaluations is also described.

EVALUATIONS AND UTILIZATIONS OF RISK IMPORTANCES

1. Definition of Qualitative and Quantitative Importance

One of the most useful applications of Probabilistic Risk Analysis (PRA) is to use the PRA to identify the risk importances of design features, plant operations, and other factors that can affect risk. Risk importance as it is commonly used in PRA terminology is generally the impact on risk that a factor has. The definition and concept of risk importance will be expanded as the document unfolds.

PRA's can be used to identify the importances of risk contributors or proposed changes to systems and operations. The risk contributors can include system failures, component failures, human errors, and test and maintenance deficiencies that contribute to the present risk. The particular risk which is focused upon can be a safety system unavailability, the core melt frequency, expected latent fatalities, or various other risk measures. The risk and risk contributors which are examined will depend upon the specific objectives of the application.

PRA's can also be used to evaluate the risk importances of changes in designs, operations, or plant conditions. These changes can be either beneficial changes, such as design improvements, or can be deleterious changes, such as component wearout. The risk importance is then the impact or change in risk resulting from the input change. The particular changes which are evaluated will again depend upon the objectives of the PRA utilizations.

All the importances which are determinable from a PRA can be grouped into two classes:

---

1. Qualitative importances

and

2. Quantitative importances.

Qualitative importances are importances of risk contributors and importances of changes which are derived from the qualitative, logic structure of the PRA. The logic structure of the PRA includes the fault tree and event tree models, the failure combinations causing undesired events (the minimal cut sets), and the success paths preventing undesired events (the minimal path sets). The qualitative information in a PRA provides valuable criteria by which to evaluate importances of risk contributors and changes.

The quantitative importances are the importances of risk contributors and changes which are derived from the quantitative results of the PRA. The quantitative importances can utilize the estimated system failure probabilities, accident sequence frequencies, core melt frequency, or even the entire accident frequency versus consequence curve. The quantitative importances can provide more detailed information than the qualitative importances, however, the quantitative importances are also subject to more uncertainties associated with the quantification. Later sections will describe the evaluation of qualitative and quantitative importances.

2. Distinction Between Risk Reduction and Safety Assurance

Before discussing the evaluation of importances, it is useful to first identify the general uses of importances. In using structural or quantitative importances, one can have either one of two general objectives:

---

1. Risk reduction

or

2. Safety assurance.

The objective of risk reduction is to make the present risk lower. This implies that some decision has to first be made that the present risk level is unacceptable. Even if cost benefit analysis is used to show a positive net benefit from the risk reduction, in order to carry out any action there still has to be a decision made that the present risk level is

unacceptable because a positive cost benefit can be shown for a risk reduction. Examples of risk reduction activities which have been carried out are present plant backfitting programs and the plant changes that were instituted after the Brown's Ferry fire and the Three Mile Island accident.

In evaluating risk importances for risk reduction, the focus is on identifying the dominant contributors to present risk. Ways for reducing these contributors are then assessed for their cost, effectiveness, and other criteria.

The objective of safety assurance, or reliability assurance as it is sometimes called, is to assure that risk does not increase and is as low as the PRA indicates it is. There is no predetermination as in the risk reduction case that risk should be reduced because it is unacceptable or provided a positive net benefit can be demonstrated. The prime objective of safety assurance is to protect against a risk deterioration. Examples of safety assurance activities are plant inspection activities performed by NRC inspectors and reliability assurance programs carried out by the plants.

When evaluating importances for safety assurance uses, the focus is on those conditions which have the greatest impact, or importance, in increasing risk. The importance of a safety assurance activity or safety assurance feature is consequently the impact it has in keeping the risk from increasing.

In a plant, risk reduction and risk assurance activities can both be carried out concurrently. There are also relationships between risk reduction and risk assurance activities. If a risk assurance activity finds an increased risk condition, then the situation and objective changes. If the increased risk is assessed to be significant then the objective becomes now one of risk reduction. Similarly, a risk reduction activity, once a risk reduction change is instituted, will transform to safety assurance activities to assure the change is effectively instituted and is maintained.

Physical activities, or functions, can thus have both risk reduction and risk assurance aspects. It is useful however to separate the risk reduction and safety assurance objectives. This is particularly useful for importance evaluations since the type of importance which is applicable will depend not only on the general objective, but also on the specific problem

being addressed. The distinctions between risk reduction importances and risk assurance importances will be amplified in later sections.

3. Evaluation of Qualitative Importances

As was stated, qualitative importances are importances derived from the logic structures of the PRA. The logic structures which will be specifically examined for their importance information are:

---

1. The event tree and system models themselves
2. The critical failure combinations, or minimal cut sets, of the PRA
3. The failure combinations which are not critical but will cause significant risk increases

and

4. The success paths, or minimal path sets, of the PRA.

Each of these logic structures will be described in a following section. A separate section will demonstrate applications of these discussions. Finally, at the end of this chapter, a discussion will be given how importance information can be used to categorize the risk significance of issues which exist or occur at plants.

3.1 The Event Tree and System Models

The event trees and fault trees developed in the PRA are the first sources of information on what is important to risk. The event trees and fault trees are logic representations of what is necessary to cause undesired events to occur. The event trees define the specific sequences of failures that are necessary for core melt or radioactive release to occur. The failures in the accident sequences can be safety function failures or safety system failures depending upon the resolution of the event trees. The fault trees define the specific component failures that are necessary for a particular safety function or safety system to fail.

The problem with the original event trees and fault trees in the PRA is that they are cumbersome and are often expressed in PRA jargon. The original event trees and fault trees were developed as base models for the purpose of evaluating all potential contributors to risk that were postulated. These models were not generally edited after the analysis was performed to make them utilizable in other applications.

The PRA models can be edited and accessed in several ways:

1. Show only the dominant contributors
2. Present the models in a hierarchical way

and

3. Put the models on a personal computer for easy access.

Keeping only the dominant contributors reduces the models significantly; oftentimes over 75 percent of the contributors are not risk significant. Care must be taken in extracting the dominant contributors since what is dominant will depend upon the application. This is generally not a problem since the contributors can be straightforwardly organized according to different applications and objectives. For example, for accident prevention, the dominant contributors to core melt frequency and to system unavailability would be the focus. For consequence mitigation, the dominant contributors to health consequences, given a core melt, would be the focus.

Arranging the models in a more hierarchical way than is presented in the PRA can greatly organize the information to make it more understandable. Accident sequences leading to core melt or core damage can be presented in terms of the initiating event and failures of safety functions which are required. Failures of safety functions can be presented in terms of failures of safety systems which cause the function to be unavailable. Finally, failures of safety systems can be presented in terms of necessary train failures and component failures. In this way, the user can step through the risk contributors to the level and detail desired.

As an efficient way of accessing the PRA's, the models and evaluations can be placed on a personal computer (PC). The plant operator or inspector could then simply query the models to obtain risk information. Having the models on a PC would be particularly useful for identifying risk information, such as dominant contributors, for particular plant statuses.

The PRA jargon problem can be addressed by describing events in English. Even if acronyms and abbreviated names are used, they can be suggestive of the events. Effective display and communication of the PRA models is not given the attention it should in PRA's. Personal computers can also be helpful here with user menus and help commands.

The event tree and fault tree models, in edited and accessible form, can provide a key tool for educating plant personnel and inspectors on how to think of the plant in terms of risk. This knowledge can be used as a foundation for how the personnel then perceive events and issues in terms of their risk significance.

In extended applications, the models can serve as the bases for expert systems programs which plant personnel and inspectors can query to determine risk implications of a given plant status, an occurring event, or a proposed design or operations change. The discussions in later sections can in fact be viewed as further steps toward these expert systems approaches.

To conclude this section, the displays on the following pages are samples of ways plant risk information could be presented. The displays are still rough and are only indicative of what might be done if effort were devoted to this area. The displays are also only samples, for example, they could be snapshots of screen displays from a plant risk model program on a personal computer. The displays were developed from the IREP PRA on Arkansas Nuclear One[1].

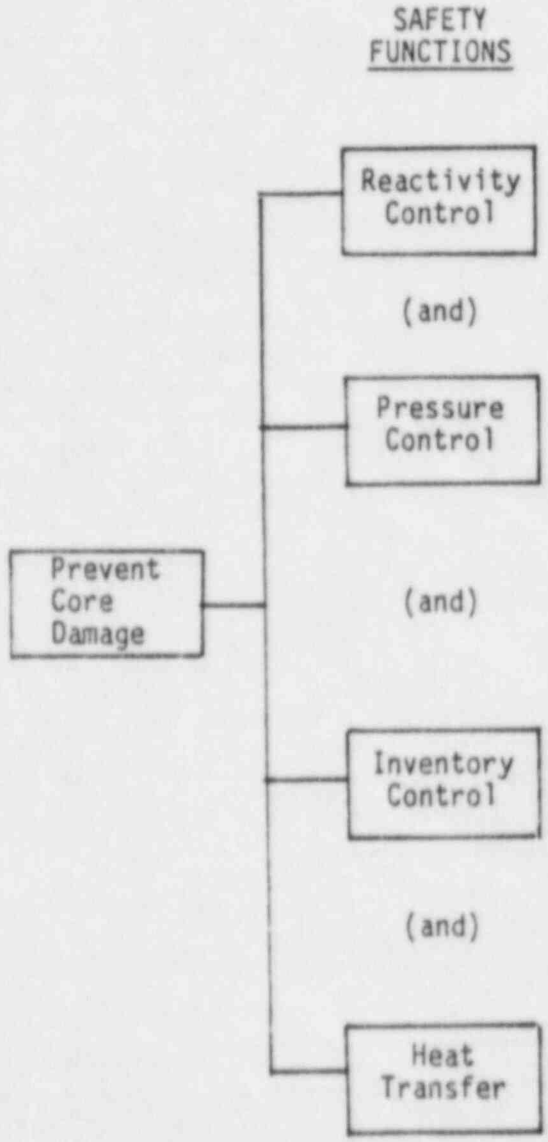


FIGURE 1. DISPLAY OF REQUIRED SAFETY FUNCTIONS AT ARKANSAS NUCLEAR

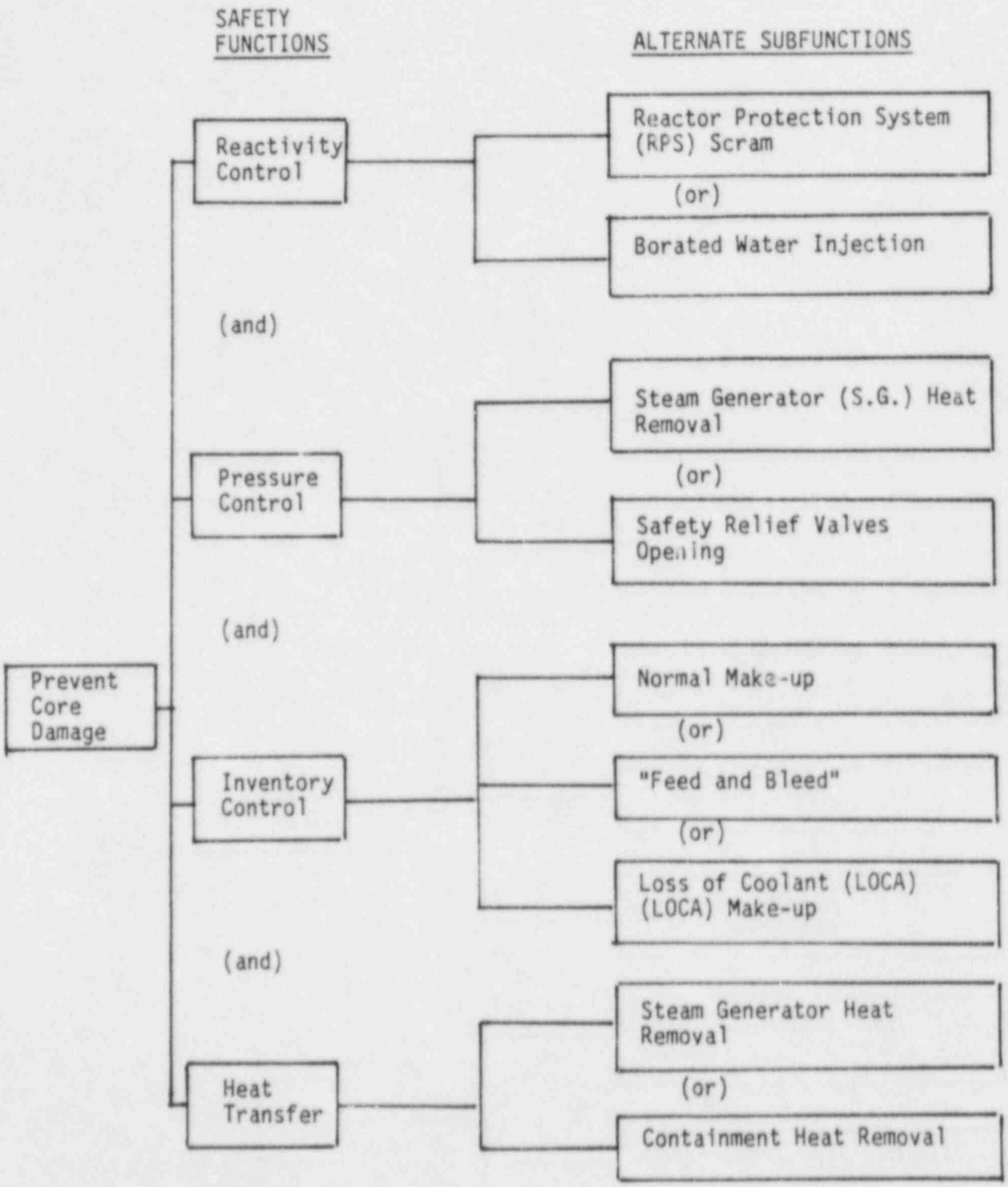


FIGURE 2. DISPLAY OF ALTERNATE SUBFUNCTIONS FOR ACHIEVING THE REQUIRED SAFETY FUNCTIONS AT ARKANSAS NUCLEAR

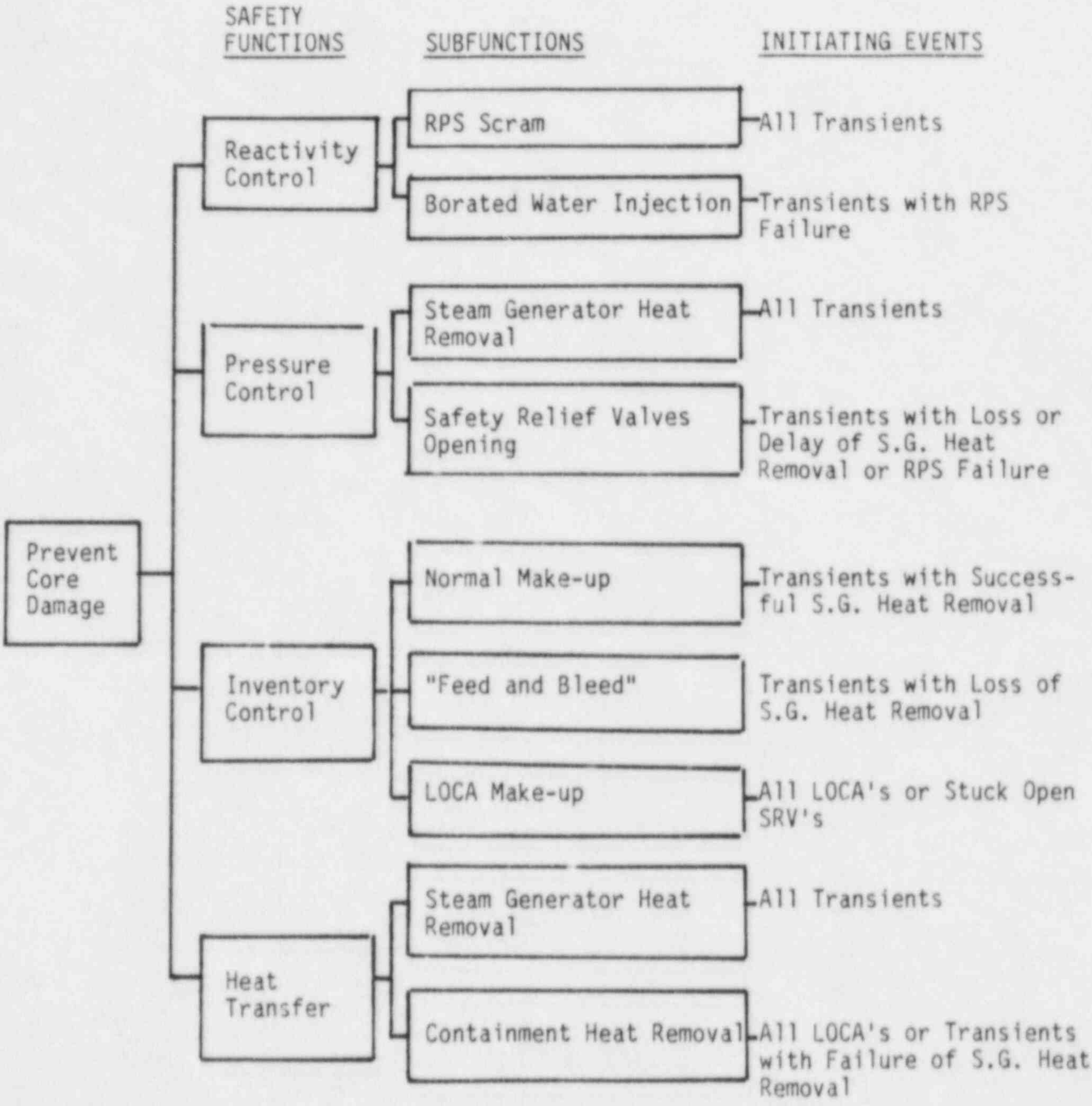


FIGURE 3. INITIATING EVENTS WHICH DEMAND THE SUBFUNCTIONS AT ARKANSAS NUCLEAR

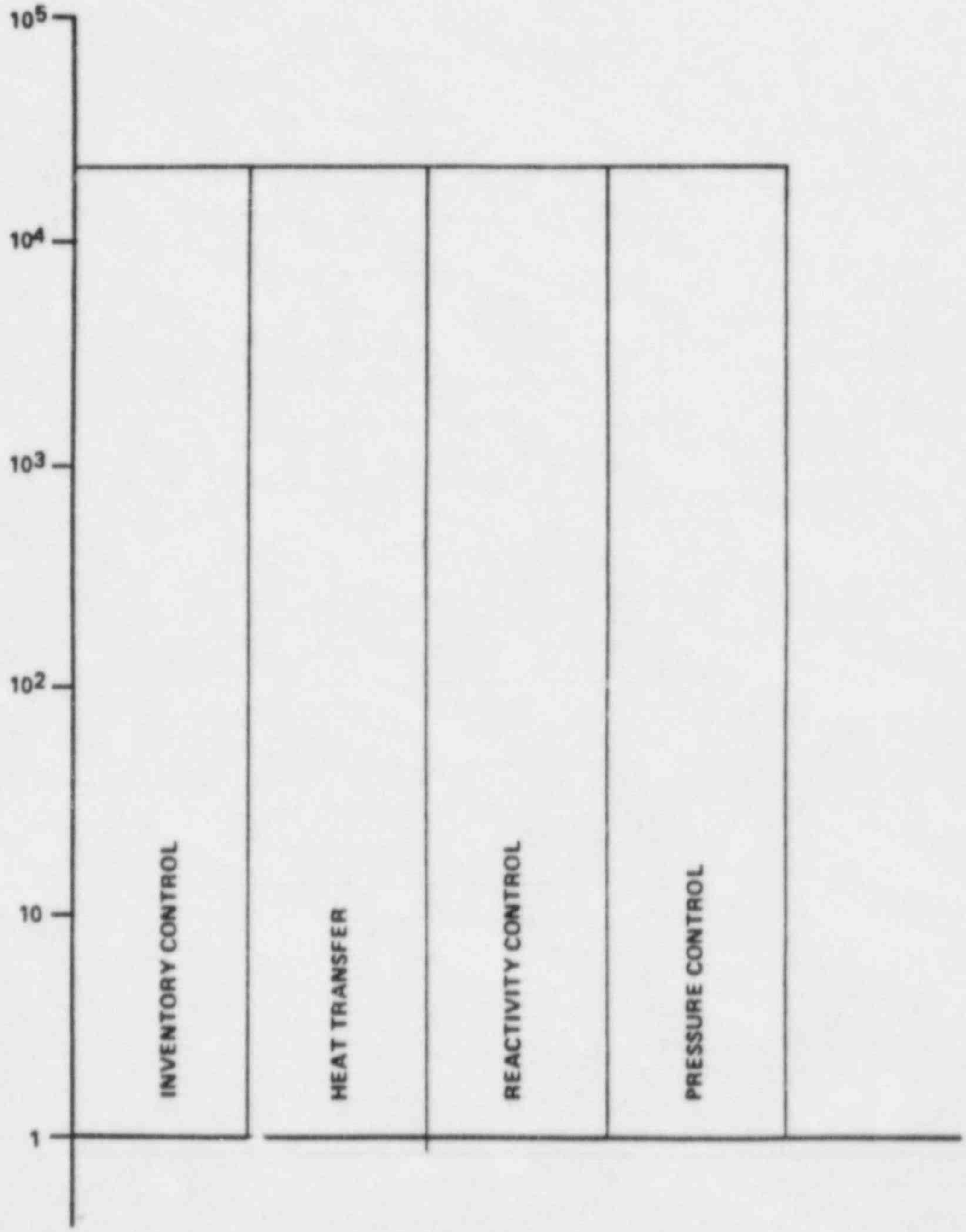


FIGURE 4. FACTOR BY WHICH THE CORE MELT FREQUENCY WOULD INCREASE IF A PARTICULAR SAFETY FUNCTION WERE UNAVAILABLE

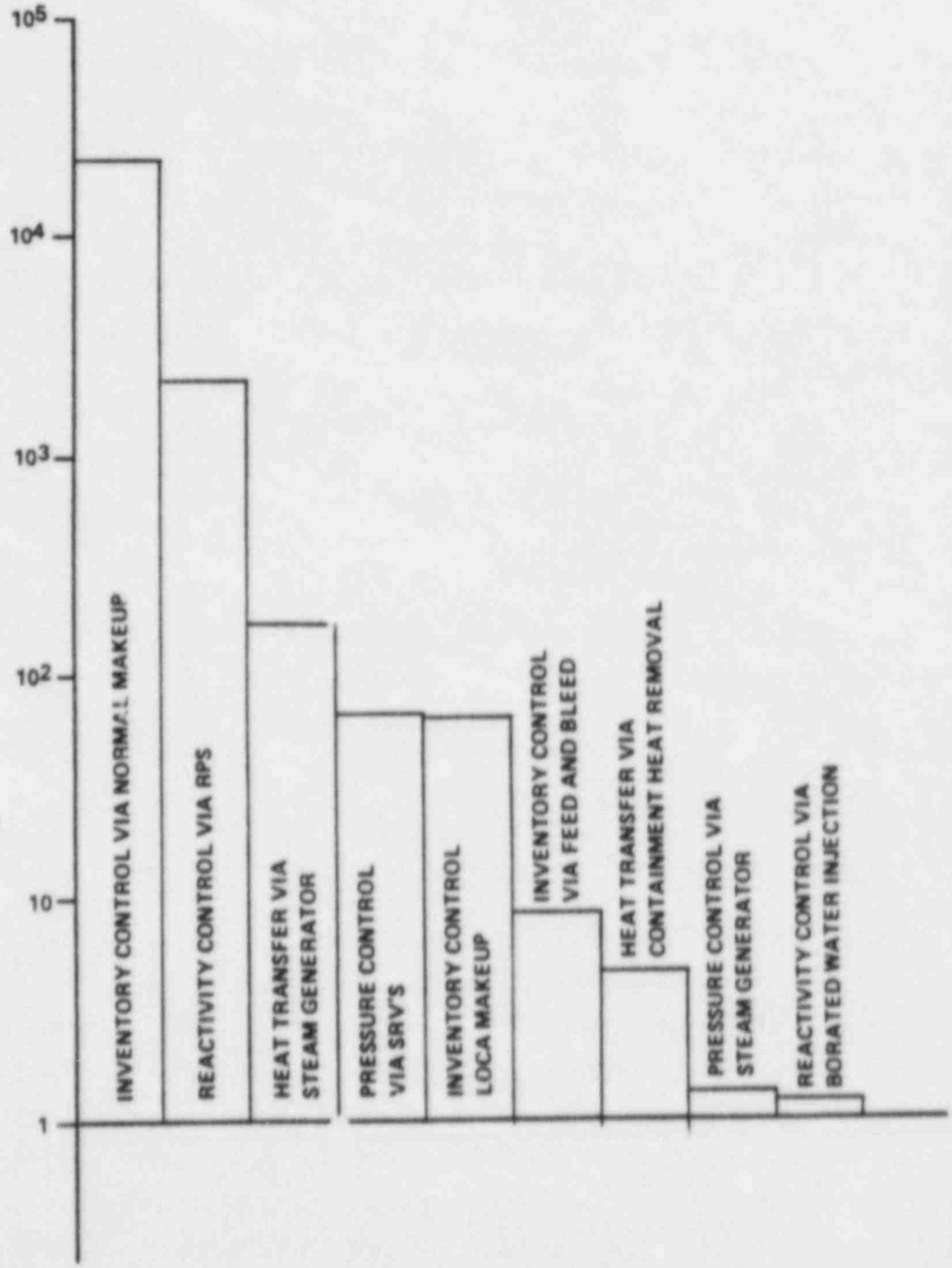


FIGURE 5. FACTOR BY WHICH THE CORE MELT FREQUENCY WOULD INCREASE IF PARTICULAR SUBFUNCTIONS WERE UNAVAILABLE

3.2 The Critical Failure Combinations, or Minimal Cut Sets

A critical failure combination, or minimal cut set as it is called in PRA terminology, is a smallest combination of component failures that will result in an undesired event. The undesired event can be a system failure, function failure, or an accident sequence occurrence.

Consider the simple series system below. The system could represent for example a leg of a safety system. This simple system has three single component min cut sets. This simply says that if any of the components fail, then the system fails.

Series System

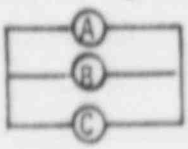
Min cut sets

A

B

C

Parallel System



Min cut sets

A·B·C

For the parallel system above, there is one three component min cut set, which says that all the components must fail for the system to fail.

The minimal cut sets, or min cut sets for short, for a general system failure are all those combinations of component failures that result in system failure. Each component failure combination is unique and is minimum in that all the component failures in the combination are necessary to cause system failure in this particular way. An example of a system min cut set is the failure of two electric pumps and the failure of a steam driven pump which fail the auxiliary feedwater system; the min cut set in this case consists of three component failures.

The min cut sets of a safety function are the combinations of component failures which result in the safety function failure. The min cut sets of an accident sequence are the component failure combinations which result in the accident sequence occurring.

The PRA provides the min cut sets of each system failure, each function failure, and for each accident sequence occurrence. There are only a finite number of min cut sets for each undesired event (system failure, function failure, etc.). The component failures in a min cut set are the lowest level failures in the PRA. The component failures can be actual component hardware failures (e.g., a pump failure) or can be human errors or operational causes of failures ("component" is thus used in a general sense here). The min cut sets are usually ordered with regard to the number of components in the min cut set and the min cut sets are usually truncated after the number of component failures in the min cut set exceeds some value. Minimal cut sets are described in more detail in the Fault Tree Handbook[2] and in the PRA Procedures Guide[3].

The min cut sets are the key quantities used in quantifying the PRA. However, the min cut sets also provide qualitative, structural information which can be used to identify important component failures and important situations that can lead to high risks. Single component min cut sets for a system, for example, are single component failures which result in system failure. NRC's single failure criterion does not allow particular types of single failures and the min cut sets can be checked to assure that there are no single cut sets.

One of the uses of min cut sets that can be particularly applicable to inspection is to identify systematic failure conditions which can significantly increase risk and which therefore must be guarded against. The systematic failure conditions are identified by the following considerations.

Based on reliability considerations, it is known that components which have a common failure susceptibility are subject to failure from one common cause which can fail all the components. Examples of components having a common failure susceptibility are given below:

Components Having a Common Susceptibility	The Common Susceptibility	The Common Cause Which Can Trigger All the Failures
Components in the same location	The same location	Fire in the location or another energetic event in the location
Similar components under the same maintenance	The same maintenance	An error in the maintenance

PRA's tell us something very significant about what susceptibilities to focus on. From the PRA min cut set definitions, the common susceptibilities are risk significant, or risk important, only if the susceptible components are in the same min cut set. If the susceptible components are in the same min cut set, then a common cause can trigger the component failures which because they are in the same min cut set will then trigger a system failure or accident sequence. If the susceptible failures are not in the same min cut set, then no consequences will occur from the common cause triggering the failures. Other independent failures are required which causes these contributions to be lower in probability and hence less significant.

From all the PRA's that have been performed, common cause failures of susceptible components in the same min cut set are generally dominant contributors to risk. The min cut set information from PRA's can be used in the following way in inspection and safety assurance activities to guard against common cause failures:

1. Identify those min cut sets where all the components have a common susceptibility (this is a conventional PRA procedure and common susceptibilities will be described later).
2. From the components in the susceptible min cut sets, assemble a checklist of these components for the inspector and for safety assurance programs. Components in the same min cut set can be

identified as critical groups. This list can be labeled as a common cause failure checklist.

3. Whenever one of the check-listed components have been found failed or degraded, the inspector can assure or have the plant assure that the other components in the critical group (min cut set) have not been affected by the failure cause. This assurance is especially critical if the other possible failed or degraded components are not readily detectable.
4. To further strengthen assurance against these common cause failure potentials, specific protections can be developed and be documented for each of the check-listed components and critical groups.

The above approach can be used to focus and to give substance to safety assurance activities directed to common cause failures. The min cut sets provide specific components and susceptibilities which should be guarded against because of their risk significance. The construction of a checklist simplifies implementation with knowledge of PRA's not really necessary. The instructions can be described in clear, understandable language which is not tied to PRA jargon (for example using "critical component groups" in the instructions instead of the more abstruse "min cut sets"). Furthermore, if the checklists are programmed on a personal computer they can be readily accessed to provide specific information for any given situation.

The common susceptibilities in a min cut set which can be specifically focused upon are comprehensive and can include:

---

1. All components of the same generic type (such as all pumps) in a min cut set (critical group) indicative of potentially common, critical vulnerabilities
2. All components in a min cut set in the same location
3. All components in a min cut set under the same maintenance or testing procedure

4. All human errors in a min cut set which implies that human errors alone can fail critical subsystems, systems, or functions
5. All components in a min cut set which can be exposed to a common harsh or degrading environment
6. All components in a min cut set not testable in routine surveillance testing, thereby giving a critical undetectable failure mode

and

7. All components in a min cut set tested under a common pre-op or start up procedure: if the procedure is inadequate that a critical failure mode can be untested or undetected.

The level of the min cut sets, e.g., min cut sets at the system level, determine the level at which the safety assurance against common cause failures is focused. The most comprehensive approach is to address safety assurance at various levels (system, function, and accident sequence) to provide a multi-level multi-pronged protection. A documentation can be performed to validate that assurance has been taken against the identified common cause susceptibilities.

3.3 Vulnerable Plant States

The min cut sets can also be used to identify plant conditions during which the plant is at higher risk and is more vulnerable to accident occurrences. From a safety assurance standpoint, it is important that these high risk conditions are first of all recognized. When these conditions occur, extra precaution can then be taken and efforts can also be focused at moving the plant from this high risk state. Furthermore, where feasible, specific procedures can be instituted to avoid these high-risk situations. The role of the inspector can be particularly important in assuring that these high-risk conditions are recognized and protected against.

The min cut sets are useful for identifying important, high-risk situations. When a component or components fail such that there is only one remaining unfailed component in a min cut set, then protection against the undesired event is riding on that one component. If that component were to fail, then the undesired consequences will occur. The situation will be an especially high-risk situation if the one remaining unfailed component has a higher unreliability. Active components and human errors generally have these higher unreliabilities.

The min cut sets can thus be used in the following useful ways to identify specific high-risk situations:

---

1. Identify all single failures, or single components being down, (if any) which result in one active component or one human error remaining in a min cut set. Identify also the active component or human action which is providing the sole protection against the undesired event.
2. Assemble those single failures in a checklist which identifies high-risk situations caused by single components being down and the remaining protection.
3. Identify those double failures, or double components being down, which result in one active component or one human error remaining in a min cut set. Identify also the remaining component or human action providing the sole protection against the undesired event.
4. Assemble these double failures and remaining protection in a checklist which identifies high-risk situations caused by two components being down.

The above checklists can be used in a straightforward manner by the inspector and in safety assurance programs. The checklists provide specific high-risk situations for the inspector and for the plant to be aware of, first of all. An attitude of extra vigilence and precaution should prevail during these high-risk periods. Where feasible, specific activities can also be identified which provide added assurance for the remaining component or human

action providing the sole protection. For the high risk situations caused by two components being down, procedures can also be identified for avoiding these high-risk situations, which for example can be caused by multiple components being simultaneously brought down for maintenance without an awareness of the risk implications. If the checklists are programmed on a personal computer, they can be readily accessed to show those components which should not be down at the same time and those critical components providing sole protection when a component or components are down for a given repair or maintenance.

In addition to the above approaches, the min cut sets can be used to obtain other qualitative importance information. The importance of a component to risk can be measured in a structural sense by counting the number of min cut sets of a given category which contain that component. The min cut sets can be categorized, for example, according to the size of the cut set and the types of other failures in the cut set. These other evaluations can sometimes provide useful supplemental information.

3.4 The Success Paths, or Minimal Path Sets

The success paths, or min path sets as they are called in PRA terminology, are another type of qualitative information provided by PRA's.* The min path sets are the complements of the min cut sets and are the ways the undesired event can be prevented.

A min path set is a smallest combination of components which if assured to all be up will assure that the undesired event will not occur. For a system, the system min path sets are all the unique, minimal ways that the system can be assured to be up. The min path sets of an accident sequence are all the unique, minimal ways that the accident sequence can be prevented.

By the min path set definition, only one min path set needs to be assured to be up to assure against the undesired event. A min path set being assured is again assuring that all components in the min path set are up. If the "component" is a human action, then the assurance constitutes assuring a

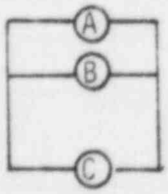
*The min path sets are also sometimes called protection sets, also an appropriate term.

successful human action. If the "component" is a plant condition, then the assurance constitutes assuring the plant condition does not exist. If the assurance is a test, then each min path set gives the combination of component tests which are necessary for an integral test of the system, of the safety function, or for prevention of an accident sequence.

The level of the min path sets (e.g., at the system level) determines the level at which overall safety assurance or integral testing is focused. PRA's can provide the min path sets for each system, each function, and each accident sequence. The min path sets can be organized and can be categorized using various criteria. The min path sets have not been standardly calculated in PRA's. This should change however with more attention now being directed to the use of PRA's for safety assurance and reliability assurance activities. The actual calculation of the min path sets is straightforward and involves standard Boolean operations.

To illustrate the min path set concept, consider the simple example shown below. For the series system, there is one min path set consisting of all the components. This simply says that to assure a series system is up, such as a leg of a safety system, all the components must be assured to be up.

Series system	Min path set
	A·B·C

Parallel system	Min path sets
	A B C

For the parallel system, there are three single component min path sets since if any component is assured to be up, the system is assured to be up.

For complex systems and accident sequences, the min path sets are not obvious and the PRA's can provide this important information. The min

path sets are key to an understanding of what constitutes an overall assurance against the undesired event or what constitutes an integral test. The min path sets can provide concrete information which can be used to focus and organize specific safety assurance activities and programs.

The min path sets can be used in inspection and in safety assurance in the following specific ways. First of all, there needs to be a recognition that to assure against an undesired event at least one min path set (success path) for that event needs to be assured. This concept is basic and can be included in education and orientation programs.

Using the min path set concepts, the following specific questions can then be asked in inspection and safety assurance activities with answers being provided by the min path sets:

---

1. Are there any min path sets (success paths) which can be assured by routine testing or monitoringΣ If so, these important testable success paths can be identified in a checklist. The component tests constituting a success path can then be inspected and be assured as an integral group.
2. If there are no success paths which can be assured solely by routine testing or monitoring, then to what degree is an integral test or overall assurance possibleΣ This can be answered by identifying those key components which are not testable but are necessary for an overall success path assurance.
3. With regard to the key components, which are not testable by routine testing or monitoring, can success path assurance be provided by alternate means such as
   a. testing at shutdown
   b. testing at pre-op or start up
   c. equipment qualification tests
   d. plant demands (transients)Σ

   If so, the specific means or events should be identified as being key to overall success path assurance. Inspection and

quality assurance can be focused on these key activities or events.

4. If there are no success paths which can be assured by any type of direct testing (or plant demands), then what indirect assurance is needed for an overall success path assurance? This indirect assurance can include, for example, calculational techniques or sampling techniques. This indirect assurance can be identified as being critical for overall success path assistance and can also be the focus of inspections and reviews.

The above approaches can be modified or can be tailored in various ways. The above approaches focus on the key issues in safety assurance which is the identification of success paths and what constitutes assurance of a success path. Attention is systematically directed towards those success paths which can be effectively tested or assured, and to those components which are key to integral testing and overall assurance. The above approaches can be useful even if they're only used to help organize and structure present safety assurance activities. If programmed on a personal computer, the success paths can be readily accessed for any plant status providing timely information on what success paths are now available.

In addition to the above approaches, other evaluations of the min path sets can be performed. The importance of a component to success path assurance can be indicated by counting the number of success paths which contains the component. Instead of considering all the success paths, success paths of a given category (e.g., testable success paths) may instead be considered. The fraction of success paths containing the component is a simple indicator of the component's importance with regard to the success paths. The success paths can also be ordered according to the ease and effectiveness by which they can be assured. These additional evaluations can provide useful supplemental information.

3.5 Demonstration of Qualitative Importance Utilizations

The displays on the following pages demonstrate utilizations of qualitative importances as discussed in the previous sections. The displays give safety assurance checklists which can be utilized by the inspector or plant personnel. The PRA for Arkansas Nuclear (ANO-1) is again used as the information source. The Emergency Feedwater System is specifically focused upon because of its large impact on core melt frequency. (The event tree and system models discussed in Section 3.1 would show this large impact for the Emergency Feedwater System.)

The displays again are by no means comprehensive and are meant only to be samples. The displays furthermore are not in the optimal user-friendly form they could be, but they will serve the purpose here. The displays again could be a snapshot of pages in a safety assurance manual. They could also be snapshots of screen displays from a computer program on a personal computer.

The displays are fairly self-explanatory. Figure 6 identifies those critical groups (min cut sets) of components which are susceptible to common cause failures because of the similarity of components. Figure 7 identifies those specific components to check when a given component has failed: on a personal computer, such a checklist could be quickly accessed to focus inspection and safety assurance when an incident has occurred.

Figure 8 is a display of an operability checklist based on vulnerable plant states. Again, such a checklist could provide timely and critical information on what key components to assure operable when a given component is down for maintenance. Figure 9 is a display of what assurances or checks are needed to provide integral assurance that the emergency feedwater system is up; Figure 10 is a graphic display of integral assurance requirements. The integral assurance requirements are based on the success paths and could be further categorized as was discussed. Assurance requirements and options could also be obtained for given plant statuses identifying success paths when a given component is down.

TITLE: COMMON CAUSE CHECKLIST FOR EMERGENCY FEEDWATER SYSTEM

DATA: Groups of components which are susceptible to the same failure cause and which if all fail will fail EMERGENCY FEEDWATER SYSTEM

DESIRABLE ASSURANCE ACTION: Assure that components in each group are protected from common or systematic failure causes especially common maintenance or testing errors and common environmental stresses

RESULTS: CRITICAL COMPONENTS AND FAILURE MODES

GROUP 1. MOTOR DRIVEN PUMP 1 (INOPERABLE)
MOTOR DRIVEN PUMP 2 (INOPERABLE)

GROUP 2. MOTOR OPERATED VALVE 1 (FAILED CLOSED)
MOTOR OPERATED VALVE 2 (FAILED CLOSED)

GROUP 3. MOTOR OPERATED VALVE 3 (FAILED CLOSED)
MOTOR OPERATED VALVE 4 (FAILED CLOSED)

GROUP 4. CIRCUIT BREAKER 3 (FAILED OPEN)
CIRCUIT BREAKER 4 (FAILED OPEN)

FIGURE 6. DISPLAY OF A COMMON CAUSE FAILURE CHECKLIST FOR ARKANSAS NUCLEAR

TITLE:	COMMON CAUSE CHECKLIST WHEN A COMPONENT IS FOUND FAILED
DATA:	Other components which are also most likely to be failed and if failed will cause significant risk increases
DESIRABLE ASSURANCE ACTION:	Assure that components in each group have not been affected by the failure of the given component
QUERY:	Failed component? Motor Operated Valve 1 System EMERGENCY FEEDWATER

RESULTS:	OTHER SUSCEPTIBLE COMPONENTS	CONSEQUENCES OF ADDITIONAL FAILURES
GROUP 1.	MOTOR OPERATED VALVE 2 (FAILED CLOSED)	EMERGENCY FEEDWATER FAILED
GROUP 2.	MOTOR OPERATED VALVE 4 (FAILED CLOSED) (AND) MOTOR OPERATED VALVE 5 (FAILED CLOSED)	EMERGENCY FEEDWATER FAILED
GROUP 3.	MOTOR OPERATED VALVE 6 (FAILED CLOSED) (AND) MOTOR OPERATED VALVE 7 (FAILED CLOSED)	EMERGENCY FEEDWATER FAILED

IF EMERGENCY FEEDWATER IS FAILED, CORE MELT FREQUENCY INCREASES BY A FACTOR OF 70

FIGURE 7. DISPLAY OF A COMMON CAUSE CHECKLIST FOR A FAILED COMPONENT AT ARKANSAS NUCLEAR

TITLE:	OPERABILITY CHECKLIST WHEN A GIVEN COMPONENT IS DOWN FOR REPAIR OR MAINTENANCE
DATA:	Other critical components which if also down will cause significant risk increases
DESIRABLE ASSURANCE ACTION:	Assure that other critical components are up and operable during the repair or maintenance
QUERY:	Downed component? Motor Driven PUMP 1 System? EMERGENCY FEEDWATER

RESULTS COMPONENTS TO CHECK	CONSEQUENCES IF DOWN
1. MOTOR DRIVEN PUMP 2 (OPERABLE)	EMERGENCY FEEDWATER FAILED
2. TURBINE PUMP (OPERABLE)	EMERGENCY FEEDWATER FAILED
3. TURBINE CONTROL VALVE (OPEN)	EMERGENCY FEEDWATER FAILED
4. MOTOR OPERATED VALVE 2 (ABLE TO OPEN)	EMERGENCY FEEDWATER FAILED

IF EMERGENCY FEEDWATER IS FAILED, CORE MELT FREQUENCY INCREASES BY A FACTOR OF 70

FIGURE 8. DISPLAY OF OPERABILITY CHECKLIST WHEN A COMPONENT IS TAKEN DOWN AT ARKANSAS NUCLEAR

TITLE: INTEGRAL ASSURANCE REQUIREMENTS FOR EMERGENCY FEEDWATER SYSTEM

DATA: Components which need to be operable for Emergency Feedwater to be operable

DESIRABLE ASSURANCE ACTION: Assure the identified components or trains are operable by testing or inspection

RESULTS: FOR EMERGENCY FEEDWATER TO BE OPERABLE

TANK FILLED

(and)

MANUAL VALVE 1 OPEN

(and)

TRAIN 1 OPERABLE (OR) TRAIN 2 OPERABLE

FOR TRAIN 1 TO BE OPERABLE:

MOTOR OPERATED VALVE 1 CLOSED AND OPERABLE

(and)

MOTOR DRIVEN PUMP 1 OPERABLE

(and)

OFFSITE POWER AVAILABLE (OR) DIESEL GENERATOR OPERABLE

(and)

CIRCUIT BREAKER 3 OPERABLE

FIGURE 9. DISPLAY OF INTEGRAL ASSURANCE REQUIREMENTS AT ARKANSAS NUCLEAR

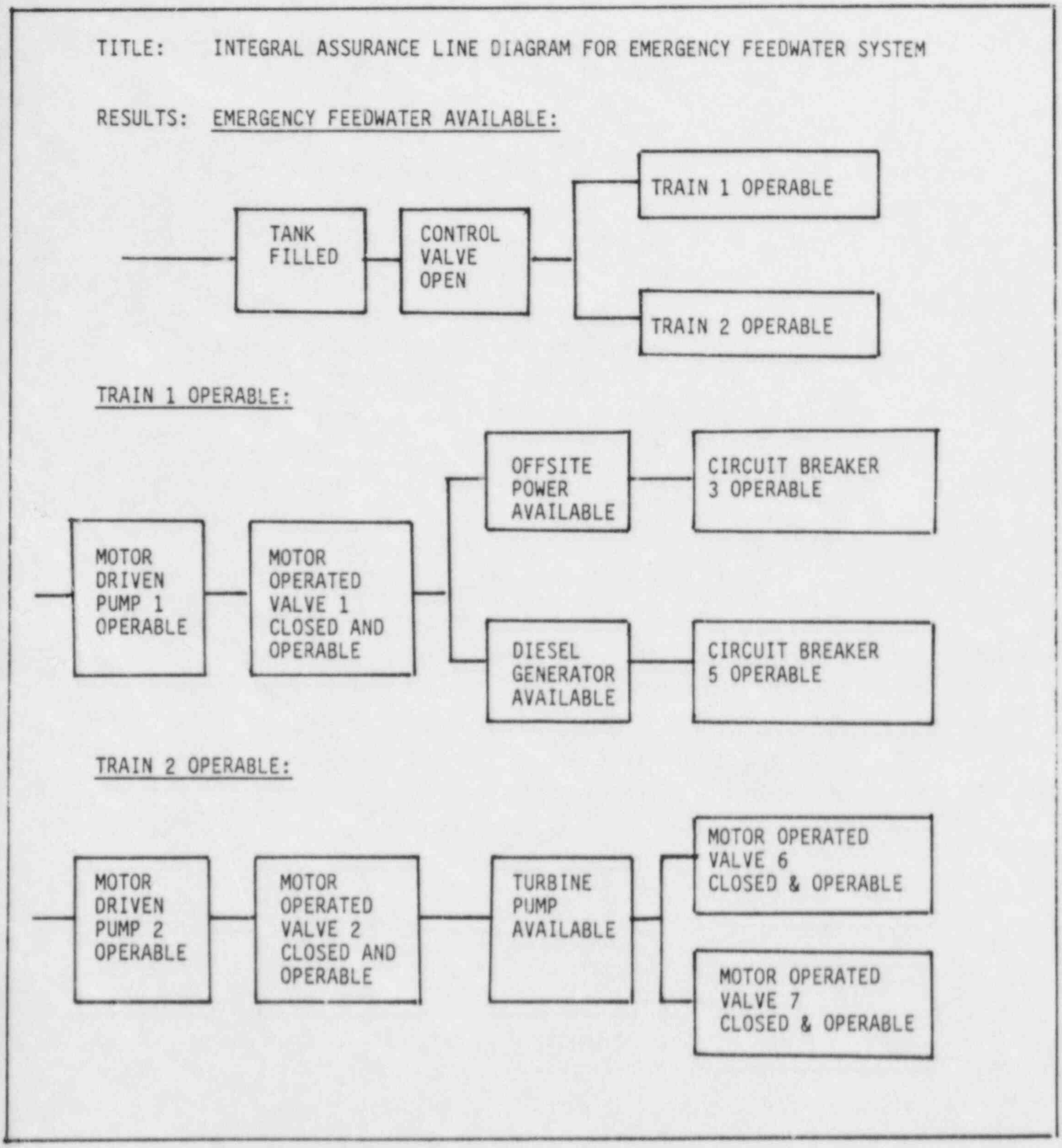


FIGURE 10. GRAPHIC DISPLAY OF INTEGRAL ASSURANCE REQUIREMENTS AT ARKANSAS NUCLEAR

3.6 Use of Qualitative Importance Information to Categorize the Risk Importance of Issues

As a final addition to the discussion of qualitative importances, it is useful to point out that the previous qualitative importance information can be used to help categorize the risk importance of issues that exist at a plant. This application was previously indicated, but it is worthwhile to expand upon it a bit because it is somewhat different in focus from the previous applications.

Even though categorizing issues has a somewhat different focus, it uses the same basic qualitative importance information as the previous applications. The basic categorizing rule is straightforward: Any issue which impacts a structurally important risk contributor is itself risk significant and deserves attention. All those risk contributors which were identified as being structurally important using the approaches in the previous sections can therefore serve as a basis for identifying risk important issues.

As a specific example, consider those issues which are associated with incidents which have occurred. The previous approaches and checklists can be used to identify those incidents which are directly risk significant. These risk significant incidents can be categorized into two types:

1. Those incidents which cause failure of one of those critical components or systems identified as leaving the plant in a risk vulnerable state; when one of these components or systems has failed, the risk has significantly increased

or

2. Those incidents which cause two or more components of a critical group to fail which is indicative of critical common mode or systematic failures.

The incidents can then be reviewed to determine if they can be placed in either of the above two categories. If they can, they are directly risk significant. For more specific guidelines, the above categories can be decomposed into more specific identifications in the same way that the previous checklists were. Also, incidents which do not fit into the above

categories can be reviewed to see if they could indirectly impact the risk significant categories (e.g., the failure cause could also apply to the risk significant categories). There are thus a number of useful ways in which qualitative importance information can help determine what is important.

4. Evaluation of Quantitative Importances

In addition to qualitative importances the other kinds of importances obtainable from PRA's are quantitative importances. Quantitative importances are importances derivable from the quantitative results of the PRA. Because they are based on quantitative results, quantitative importances can provide more detailed information than qualitative importances. The quantitative importances, if defined correctly, will not be inconsistent with the qualitative importances, but instead will supplement and extend the importance information. Furthermore, with careful utilizations, the quantitative importances will be robust to the uncertainties associated with the PRA quantification.

As was stated at the beginning of the report, risk importance is generally the impact that a factor has on risk, where the "factor" can be a design feature, operational procedure, an activity, or a phenomenon. The quantitative risk importance is the impact that a factor has on the quantified risk.

To obtain meaningful quantitative risk importances, we must first define meaningful ways of actually calculating the importances. This involves defining the importance measure we will use. We must also identify the specific risk characteristic, such as the core melt frequency, which we will use to calculate the risk impacts. Furthermore, we must clearly identify the specific factors whose importances, or impacts, we will evaluate. Finally, we must define the plant status, or plant state, for which the importances will be evaluated.

In the following sections we describe understandable and consistent ways of calculating risk importances. The risk importances are comprehensive and are adaptable to any specific problem. We explicitly show the differences

between importances calculated for safety assurance purposes and those calculated for risk reduction purposes. The discussions show how the comprehensive importance evaluations specialize to already published importances (e.g., the Birnbaum importance) and the problems for which these specialized importances are applicable. This development of importance measures is also a generalization and extension of our previous work on importances[4,5].

We discuss the use of different specific risk characteristics in evaluating importances. The role of plant status in importance evaluations is described. The discussions also show how uncertain events and a range of possible plant states can be incorporated into the evaluations. We will demonstrate importance evaluations for specific problems. We will again use the Arkansas Nuclear PRA as an example. Finally, PRA uncertainty considerations are addressed with regard to implementations of the importance evaluations.

4.1 Development of the Basic Importance Measures

We will follow a line of reasoning which starts from basic considerations and which produces understandable, soundly based importance measures. In the most basic representation, the importance or impact of any factor to risk is the change in risk introduced by the factor:

The importance of a factor to risk	=	The change in risk introduced by the factor	(1)

This basic, natural definition is the foundation of all subsequent considerations.

Equation (1) says that to measure the importance, we need to measure the change in risk. The most common measures of risk changes are differences in risk or ratios of different risk values. The change in risk either can be a decrease in risk if the factor is beneficial or can be an increase in risk if the factor is detrimental.

If the factor is beneficial and tends to reduce risk, then the risk will increase if the factor is not present. Measuring the risk change as a

difference in risk (the ratio will work equally well), we then can naturally express the importance of a beneficial factor as:

The importance of a beneficial factor	=	The decrease in risk when the factor is present		(2)
	=	The risk with the factor out	- The risk with the factor in	(3)

The above expression applies whether the beneficial factor is already present or is a new factor (a modification) being considered.

In the same manner as above, the importance of a detrimental factor can be represented as:

The importance of a detrimental factor	=	The increase in risk when the factor is present		(4)
	=	The risk with the factor in	- The risk with the factor out	(5)

Again the detrimental factor can either be already present or can be a factor which could be introduced.

The above simple but powerful formulations are the bases for all the risk importances that we will subsequently derive. In the above formulations, the only difference between the importance of a beneficial factor and a detrimental factor is the way in which the risk difference is defined. The formulas are defined so that importances are positive. We could as well have used one formula (either (2) or (3)) and had both positive and negative importances. We, however, feel that it is more straightforward to deal with positive importances. If we don't know whether a factor is beneficial or detrimental, we can always use one of the above formulas, for example Equation (2) considering the factor as tentatively being beneficial. If the importance is negative, we simply change the sign and identify the factor as being detrimental. These points concerning the sign conventions for the importances are minor and do not impact the basic formulation for the importance.

It should be noted that the above formulations apply for any specific risk characteristic that we select to calculate the importance. For importances for accident prevention, the risk characteristic could be the core

melt frequency, system unavailability or some other accident likelihood related characteristic. For accident mitigation importances, the risk characteristic would be some specific consequence measure such as the expected manrem given an accident.

4.2 Examples of Importance Representations

Before we consider actual calculation of the importances, it is useful to show how the above straightforward and logical formulations can be used to represent the importance of any design feature, any activity, or any phenomenon. In the following examples we will use these symbols:

$$I\ (\text{factor}) = \text{the importance of the factor} \quad (6)$$

$$R\ (\text{factor in}) = \text{the risk with the factor} \quad (7)$$

and

$$R\ (\text{factor out}) = \text{the risk without the factor} \quad (8)$$

Therefore, the general importance formulas can be expressed as:

$$I\ (\text{beneficial factor}) = R\ (\text{factor out}) - R\ (\text{factor in}) \quad (9)$$

and

$$I\ (\text{detrimental factor}) = R\ (\text{factor in}) - R\ (\text{factor out}) \quad (10)$$

In the examples, the factor will be replaced by the specific design feature, activity, or phenomenon whose importance is being evaluated.

Importance of a Safety System

$$I\ (\text{safety system}) = R\ (\text{safety system not present}) - R\ (\text{safety system present}) \quad (11)$$

The importance of a particular safety system is the risk change with the system present and not present. The system can be an existing system or a

proposed new system. System importances are useful in categorizing in a general manner which existing systems are more risk important than others. The system importance can also identify the benefit of a proposed system modification. When the new system is introduced, modifications of other systems may be required and necessary changes should be incorporated into the risk evaluations. These modifications effectively define the plant status with the system present and not present.

Importance of a Surveillance Test

$$I\ (\text{surveillance test}) = R\ (\text{without the surveillance test}) - R\ (\text{with the surveillance test}) \qquad (12)$$

Here the surveillance test is tentatively assumed to be beneficial with the risk being higher with the test not there. If under this assumption, the importance is negative, then we would reverse the sign and declare the test to be detrimental with the risk increase given by the importance. Surveillance test importances are useful in determining which tests are most important in order to check to see that they're performed. The importance of the test is with respect to a defined plant status, for example considering other existing surveillance tests.

Importance of an Efficient Test

$$I\ (\text{efficient test}) = R\ (\text{with inefficient test}) - R\ (\text{with efficient test}) \qquad (13)$$

The importance of an efficient test is not necessarily the same as the importance of having a given test versus not having it which was addressed previously. Here the importance is with respect to having different efficiencies of the test. Test efficiency importances are useful in helping to determine where effective testing is critical. To evaluate the risks, specific models are required for inefficient testing and efficient testing. Some approaches for doing this will be identified later.

Importance of a Maintenance Action

$$I\ (\text{maintenance action}) = R\ (\text{without the maintenance action}) - R\ (\text{with the maintenance action}) \quad (14)$$

Maintenance importance is similar in representation to the earlier surveillance test importance. If the maintenance action affects multiple components, then the combined maintenance effects need to be incorporated in the evaluation of the risks. Long term as well as short term effects of having and not having the maintenance would also be incorporated into the risk evaluations.

Importance of a Pre-operational Test

$$I\ (\text{pre-op test}) = R\ (\text{without the test}) - R\ (\text{with the test}) \quad (15)$$

A pre-operational, or pre-op, test is a test on systems or components before actual operation. The pre-op test helps to ensure the systems or components are up when operation begins. The pre-op test can also detect certain failures that might not otherwise be detected during operation or would be detected only after some time. The possibility of having nondetected failures as well as the failure duration time till detection can be incorporated into the risk evaluation if the pre-op test were not performed. Pre-op importances are useful in identifying which pre-op tests are most important to perform from a set of alternatives.

Importance of a Component Being Down

$$I\ (\text{downed component}) = R\ (\text{with the component down}) - R\ (\text{with the component not known to be down}) \quad (16)$$

The importance here is the importance, or risk impact, of the detrimental factor of a component being down. The downed importance is useful in determining how quickly the component needs to be brought back up. The reference risk for the importance determination (the second term on the right hand side of the above equation) is the risk with the component not known to be down. The risk with the component not known to be down is not necessarily the same as the risk with the component known to be up. The risk with the component not known to be down, for example, can include the probability of the component being down. How the reference risk is evaluated will depend upon the given plant status for the importance evaluation.

Importance of Common Cause Failures

$$\text{I (common cause failure)} = \text{R (with the common cause failure)} - \text{R (without the common cause failure)} \quad (17)$$

The importance of a common cause failure is useful in helping to determine where to focus protection and assurances against common cause failures. To determine the maximum importance common cause failures could have, an upper bound could be determined for the risk with the common cause failure. This would be useful for screening purposes. The importance is again evaluated in context of other risk contributions and for a given plant status.

Importance of Component Wearout

$$\text{I (component wearout)} = \text{R (with component wearout)} - \text{R (without component wearout)} \quad (18)$$

The last example is the importance of the detrimental factor of component wearout. Component wearout importances are useful in determining where to focus wearout prevention. The risk with component wearout can incorporate the likelihood of detecting such wearout as well as the time duration before any detection. Either local wearout of a single component or the systematic wearout of multiple components can be evaluated for their importance.

4.3 Safety Assurance Importances and Risk Reduction Importances

All the previous importance examples can be classified as either being associated with safety assurance applications or with risk reduction applications. It's very useful to know whether a particular importance is associated with safety assurance or risk reduction since this helps in interpreting and implementing the importance evaluation.

The table below is a straightforward way of differentiating between safety assurance and risk reduction importances:

	Factor Already Present	Factor Not Present
Beneficial Factor	Safety assurance importance to assure factor is present	Risk reduction importance to reduce risk by introducing factor
Detrimental Factor	Risk reduction importance to reduce risk by removing factor	Safety assurance importance to assure factor is not introduced

The above table classifies the factor as either being beneficial or detrimental and as either being already present or not. Depending upon these classifications of the factor, the importance determined for the factor is either applicable for safety assurance objectives or for risk reduction objectives. The table entries indicate the particular applicability of the importance.

As a specific example of the above table, consider the detrimental factor of component wearout considered in the previous section. Using the above table, if the wearout is already present, then the importance determined will be applicable for risk reduction objectives. The importance will indicate the risk reduction if the wearout is removed. If the wearout is not

already present, then the importance determined will be applicable for safety assurance objectives. The importance will indicate the risk increase if assurance to protect against the wearout is not taken.

As another specific example, consider the beneficial factor of an efficient surveillance test illustrated in the previous section. If the efficient test is already in place, then the importance determined will be relevant for safety assurance objectives. The importance will indicate the risk increase if assurance is not effective in maintaining the test efficiency. If the efficient test is not already in place, then the importance is relevant for risk reduction applications. The importance indicates the risk reduction if the efficient test were introduced.

4.4 Consideration of the Likelihood of Different Plant States or Conditions

The previous formulations and examples can be simply extended to handle different plant states or conditions. The actual plant status may not be definitely known for the importance evaluations or there may be different possible plant states or conditions which are to be explicitly taken into account in the importance evaluations. The probability, or likelihood, of different plant states is straightforwardly taken into account using standard probability considerations.

Let s denote a specific plant state. The plant state is defined to a sufficient degree to allow the calculation of the risk characteristic. The importance of a factor with the assumed plant state is denoted as I (factor, s):

$$I\ (\text{factor, s}) = \text{the importance of a factor assuming the plant state s} \quad (18)$$

The importance of a beneficial or detrimental factor with the assumed state s is then

$$I\ (\text{beneficial factor, s}) = R(\text{factor out,s}) - R(\text{factor in,s}) \quad (19)$$

and

$$I\ (\text{detrimental factor,s}) = R(\text{factor in,s}) - R(\text{factor out,s}) \quad (20)$$

where

$$R\ (\text{factor out},s) = \text{the risk with the factor out under the assumed plant state } s \tag{21}$$

and

$$R\ (\text{factor in},s) = \text{the risk with the factor in under the assumed plant state } s \tag{22}$$

The overall importance of the factor is then simply the importance for a given plant state weighted by the probability of the state and summed over the possible states. If

$$p(s) = \text{the probability of the plant state } s \tag{23}$$

and

$$I\ (\text{factor}) = \text{the overall importance of the factor (either beneficial or detrimental)} \tag{24}$$

then

$$I\ (\text{factor}) = \Sigma\ p(s)\ I\ (\text{factor},\ s) \tag{25}$$

where the summation Σ is over all the possible plant states s.

Equation (25) can be simply applied to either a beneficial factor or a detrimental factor by substituting the appropriate formula for I (factor, s) given by Equations (19) or (20). For example for a beneficial factor

$$I\ (\text{beneficial factor}) = \Sigma p(s)\ \ I\ (\text{beneficial factor},\ s) \tag{26}$$

$$= \Sigma p(s)\ (R\ (\text{factor out},\ s) - R\ (\text{factor in},\ s)) \tag{27}$$

Equation (27) can also be written as

$$I\ (\text{beneficial factor}) = \Sigma p(s)\ R\ (\text{factor out},\ s) - \Sigma p(s)\ R\ (\text{factor in},\ s) \tag{28}$$

Similar equations apply for a detrimental factor.

Equation (27) simply says that the overall importance of a factor is the average of the risk differences over the different plant states. Equation (28) says that the overall importance is also simply the average risk with the factor out minus the average risk with the factor in. Equation (27) is generally more useful when we wish to explicitly show how the importance (the risk difference) depends upon the plant state. The above discussions also apply to a detrimental factor with "factor in" and "factor out" being exchanged.

The above equations can be applied to the previous examples to identify the effects of specific variables. The values of the variable define the different plant states or conditions. The table below gives some of the variables which can be focused on to see the effects on the importance:

Type of Importance	Plant Conditions
Safety system importance	Status of other systems
Surveillance test importance	Status of the component
Test efficiency importance	Frequency of nondetectable failure modes
Maintenance importance	Frequency of maintenance error
Pre-op importance	Component failure or success status
Common cause importance	Frequency of common cause failure
Wearout importance	Time period of nondetection

4.5 Calculation of the Risk Importance

To actually calculate the risk importances in the previous sections, models need to be developed for evaluating the risk with the factor in (R (factor in)) and with the factor out (R (factor out)). When different plant states are considered then, in addition, the risk for different plant states

need to be modeled. The models for the risk with the factor in and the factor out may be quite different than the models which are used in usual PRA's and described in various references (for example the PRA Procedures Guide, NUREG/CR-2300). For example in evaluating wearout importances, the risk incorporating component wearout will need to be considered and this is not done in usual PRA's. The importances which are actually calculated will of course depend upon the specific models which are used to evaluate the risk difference with the factor in and factor out.

When modeling the risk importance of a factor, the first question that needs to be asked is what variable does the factor affect. In general the factor does not influence the risk directly, but instead affects a variable or variables which in turn affects the risk. For example, component wearout affects the component failure rate which in turn affects the risk.

The next question that must be asked is how does the variable affect the specific risk characteristic selected for the importance. The variables in a PRA risk analysis are the variables which determine the accident frequencies and consequences. These include initiating event frequencies, system and component unavailabilities for the accident frequencies and containment pressure and temperature, fluid flow rates, and evacuation effectiveness for the consequences.

To model the importance of a factor, we thus need to have two models--how the factor influences the risk variables and how the risk variables influence the risk. We may represent this two model, or two stage, relation as shown below:

Factor effect on the variable and Variable effect on risk ⇒ Importance of factor

The above simply says that the factor-variable relation and the variable-risk relation are needed to determine the importance of the factor.

We shall focus on accident prevention and thus focus on importances of accident frequencies, system unavailabilities, and related quantities. The approaches we will discuss can also be applied to importances for accident

mitigation. According to the above, we shall need to model the factor effect on the variable and the variable effect on risk.

The risk variables and risk characteristics for accident prevention can be organized in the way shown in Figure 11 on the next page. Figure 11 says that PRA analyses can give the core melt frequency as a function of any of the variables connected beneath it. Also any risk characteristic at an intermediate level can be expressed as a function of the variables connected below it. For example, system unavailabilities can be expressed as a function of component unavailabilities which in turn can be expressed as a function of component failure characteristics and human error characteristics contributing to the component unavailabil' y. The component failure characteristics include for example component failure rates and test intervals. The root causes at the bottom are the basic plant characteristics (environment, operation, etc.) which affect the component failure characteristics and human error characteristics.

In determining a factor's importance, the risk characteristic must be selected to evaluate the importance. The risk characteristic which is selected can be at any level. For example, a system unavailability can be selected to evaluate the importance of the factor. The importance then is the importance to the system unavailability. The lower the level of the risk characteristic, the simpler will be the importance evaluation, however, the impact on the core melt frequency will not be directly determined. This is not a problem if the lower level risk characteristic is known to be important to core melt frequency or has been determined to be important.

Once the risk characteristic is selected, it needs to be expressed as a function of the variables which are modeled as being affected by the factor. The key consideration is being able to model, or to rationalize, the effects of the factor on the variable. Since PRA's are capable of giving risk characteristics as a function of any lower level variables, the choice of the variables will thus hinge on being able to rationalize or to model the effects of the factor on these variables.

This last point is important and is worth restating. The factor effect on the variable is the driving relationship and is the relationship that needs to be identified and needs to be modeled. The effect of the

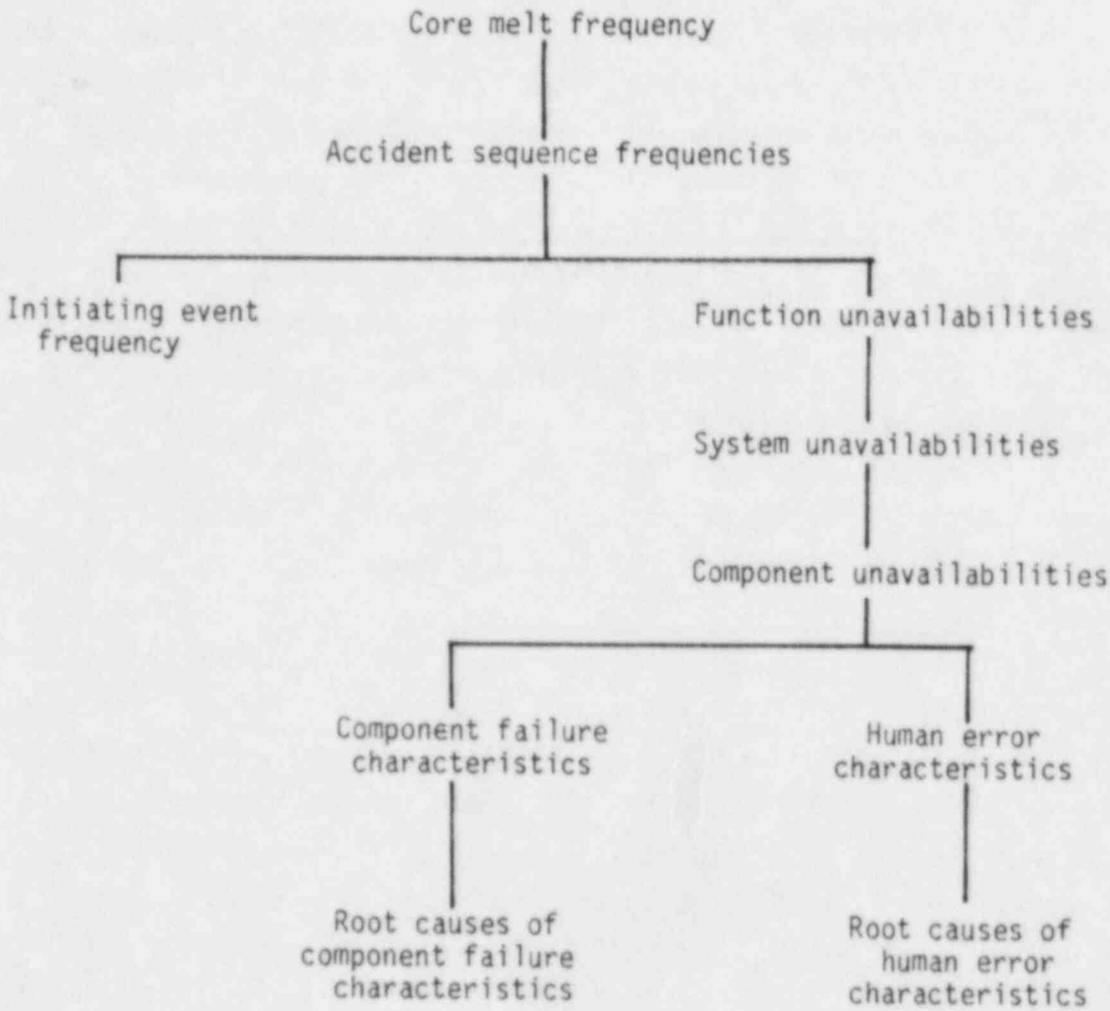


FIGURE 11. THE VARIABLES DETERMINING CORE MELT ACCIDENT FREQUENCIES

variable on the specific selected risk characteristic is then obtained from available PRA relationships. The risk importance of the factor is then straightforwardly obtained from these two models.

To actually calculate the importance of the factor, the model of the factor effect on the variable is used to determine the value of the variable with the factor in and the value of the variable with the factor out. The risk model relating risk to the variable is then used to determine the risk values corresponding to the variable values for the factor in and the factor out. The difference in the risk values is then simply the importance of the factor. The calculational approach is summarized below.

To calculate the importance of a factor:

1. Determine the variables which are affected by the factor
2. Model the change in the variables which is caused by the factor (i.e., the variable values with the factor in and factor out)
3. Determine the specific risk characteristic which is to be used for the importance evaluation
4. Relate the risk characteristic to the variables affected by the factor. Available PRA models in general can give this relation
5. Determine the risk values corresponding to the different variable values (i.e., the risk values with the factor in and out)
6. The risk importance is then simply the difference in risk values.

4.6 Example Modeling Considerations

To make the discussions in the previous sections more concrete, we shall consider the importance examples given earlier in Section 4.2. We shall first give the importance definitions using the same symbols as in Section 4.2. We shall then identify the models which need to be used to calculate the effects of the factor on the risk variables and the variables on the specific risk characteristic. In subsequent sections we shall identify specific models which can be used.

Importance of a Safety System

$$I \text{ (safety system)} = R \text{ (safety system not present)} - R \text{ (safety system present)} \quad (29)$$

Factor	Risk Variable	Risk Characteristic
System not present (or present)	System unavailability or Reconstructed accident sequences	Accident sequence frequency or Core melt frequency

The system being not present and being present can be modeled as the system unavailability being one (the system being down) and the unavailability being zero (the system being up), respectively. The risk difference can then be calculated for the two different system unavailabilities using standard PRA models. Alternatively, the system being present and being not present can be represented by constructing the accident sequences (event trees), assuming the plant design did not have the system and did have, respectively. The risk difference can then be calculated for the two sets of accident sequences. It should be noted that the two representations of the system present and not present have different applicability. The system unavailability representation (the unavailability being one and zero) is most applicable to reliability assurance activities, while the accident sequence reconstructions are most applicable to design change considerations.

Importance of a Surveillance Test

$$I\ (\text{surveillance test}) = R\ (\text{without the surveillance test}) - R\ (\text{with the surveillance test}) \qquad (30)$$

Factor	Risk Variable	Risk Characteristic
Surveillance test present (or not present)	Component unavailability	System unavailability or accident sequence frequency or core melt frequency

The component unavailability with the surveillance test present and not present can be modeled by standard reliability techniques; for the test not present component failures would be treated as being nonrepairable. Surveillance tests not performed for some period of time can be modeled using time dependent unavailability models. The component unavailability with and without the test can be calculated using these models. Once the component unavailability is determined, PRA models can be used to calculate the difference in the risk characteristic for the different component unavailabilities. The risk characteristics which can be used are the preventative, accident frequency related, characteristics.

Importance of an Efficient Test

$$I\ (\text{efficient test}) = R\ (\text{with inefficient test}) - R\ (\text{with efficient test}) \qquad (31)$$

Factor	Risk Variable	Risk Characteristic
Test inefficient (or efficient)	Component unavailability	Frequency PRA characteristics

Standard PRA models generally assume efficient testing with only test downtime considered. The possibility of not detecting certain failure modes or test

caused degradations is generally not treated. Models exist for calculating the component unavailability with an inefficient test, for different types of inefficiency. Once the different component unavailabilities are determined, PRA models can then be used to determine the difference in the risk characteristic. The risk characteristics which can be used are the frequency related characteristics, including system and function unavailabilities, accident sequence frequencies, and core melt frequency.

Importance of a Maintenance Action

$$I \text{ (maintenance action)} = R \text{ (without the maintenance action)} - R \text{ (with the maintenance action)} \quad (32)$$

Factor	Risk Variable	Risk Characteristic
Maintenance (or no maintenance)	Component failure rate	Frequency PRA characteristics

The key model which needs to be determined is the effect of maintenance and no maintenance on the component failure rate. Various existing wearout models can be used for the component failure rate effects depending upon the postulated effects of having no maintenance, or having no maintenance for a given period. If the maintenance affects multiple components, then all the impacted component failure rates would be modified. Once the component failure rates are determined for maintenance and no maintenance, the respective component unavailabilities can be determined using standard reliability formulas. Time dependent PRA models can then be used to determine the difference in the risk characteristic for the different component unavailabilities.

Importance of a Pre-operational Test

$$I \text{ (pre-op test)} = R \text{ (without the test)} - R \text{ (with the test)} \quad (33)$$

Factor	Risk Variable	Risk Characteristic
Pre-op test (or no pre-op test)	Component unavailability or system unavailability	PRA risk characteristics incorporating duration of failed component

The effect of the pre-op test can either be that the test checks for component operability and therefore determines the component is available or that it checks for system operability and determines the system is available. Also, the unavailability which is checked can be limited to the hardware contribution if human operator performance is not also checked by the pre-op test.

The degree to which component or system performance is actually validated can also be considered by incorporating testing efficiencies (checking only specific failure modes) or using time-dependent failure models (e.g., simply checking for the component or system being up versus a more thorough check which effectively renews the component or system).

Testing models exist which can be used to determine the component or system unavailability with and without the pre-op test incorporating the above considerations. Once the different unavailabilities are determined, the difference in risk characteristic can then be determined using PRA models. To explicitly incorporate likely problem areas, the likelihood of different failure states of the components (or systems) can be considered using the treatments in Section 4.4.

Importance of a Component Being Down

$$I\ (\text{downed component}) = R\ (\text{with the component down}) - R\ (\text{with the component not known to be down}) \quad (34)$$

Factor	Risk Variable	Risk Characteristic
The component being down (or not known to be down)	Component unavailability	Frequency PRA characteristics

The component unavailability with the component down is unity. The component unavailability with the component not known to be down is zero if the component is known to be up or is the usual PRA value if the component is not known to be up. As discussed previously, which is used will depend upon the particular application. With the different component unavailabilities determined, the risk difference can be determined using standard PRA models.

Importance of Common Cause Failures

$$\text{I (common cause failure)} = \text{R (with the common cause failure)} - \text{R (without the common cause failure)} \quad (35)$$

Factor	Risk Variable	Risk Characteristic
Common cause failure potential (present or not present)	Minimal cut set unavailability	Frequency PRA characteristics

The minimal cut set unavailability with common cause failures is determined from PRA approaches (e.g., beta factor approaches, shock approaches, etc.). The minimal cut set unavailability without the common cause failure potential is the standard, independent failure calculation in the PRA. With the different minimal cut set unavailabilities determined for the two situations, the risk difference can be determined using standard PRA models.

Importance of Component Wearout

$$I\ (\text{component wearout}) = R\ (\text{with component wearout}) - R\ (\text{without component wearout}) \qquad (36)$$

Factor	Risk Variable	Risk Characteristic
Component wearout present (or not present)	Component failure rate	Time dependent risk characteristics incorporating duration of wearout

The component failure rate without wearout is the standard constant failure rate treated in PRA's. The component failure rate with wearout can be modeled using existing time dependent failure rate models. The time dependent model which is selected will depend upon the specific type of wearout being considered.

With the component failure rates determined, the time dependent component unavailabilities can be determined using standard reliability formulas. The period during which the wearout can exist without detection can be incorporated in these models.

With the component unavailabilities determined, the risk difference can be determined using existing time dependent models. These time dependent models calculate the same risk characteristics as a PRA does, but with time dependency now considered. Finally, the likelihood of the wearout actually occurring can be incorporated using the approaches in Section 4.4.

4.7 Specific Models

As indicated in the previous section, the calculation of the risk importance can be complex if substantial parts of the PRA need to be completely reevaluated. For a number of problems, however, the risk importance calculations can be straightforwardly performed if specialized models can be used for the evaluations. These specialized models generally model the change in the risk characteristic as being linearly proportional to the change in the risk variable. These linear models include those cases where the effect of the factor is modeled as producing a small change, or perturbation, in the risk variable.

In this section we shall develop various specialized models to calculate the risk importance. In certain problems, these models may be sufficient; in other problems more detailed evaluations will still be needed. We will clearly identify the assumptions and limitations associated with these specialized models. These specialized models are also useful since they produce specialized importance measures which have been identified and used in the past. These specialized measures include the Birnbaum importance, the Fussell-Vesely importance, the risk achievement worth, and the risk reduction worth. By understanding the bases for these measures, one will know when, and when not, to use these measures.

In the following sections we shall show how the importance evaluations simplify when specific effects (specific models) are assumed for the factor. The key here is that in the following sections the factor is assumed to cause specific effects in the risk variables. To actually use these specialized models for a given real factor, one must first validate that indeed the factor does cause the type of effect. We shall identify the critical assumptions and the critical inputs that need to be supplied for a given specialized model. This will provide the information in determining the applicability of a given model to a real life problem. In later sections we shall demonstrate applications of the models to the Arkansas Nuclear PRA (ANO).

4.7.1 One System Unavailability Affected by the Factor

Assume that the effect of the factor is to change a system unavailability by an amount ΔQ. Instead of a change in system unavailability, the quantity ΔQ can equivalently represent a change in function unavailability. The value ΔQ can be an arbitrary value between 0 and 1 and can represent a decrease or increase in the system unavailability (i.e., the factor can be detrimental or beneficial).

Assume further that the system unavailability appears as a linear term in the formula for the risk characteristic. This will be generally true if the system is a frontline or support system which appears in the event trees (accident sequences) and whose failure is a contributor to core melt or to an accident.

Under the above assumptions, using the general PRA formulas, the importance I(f) of the factor can be expressed as:

$$I(f) = (R(1) - R(0))\ \Delta Q \qquad (37)$$

where

$R(1)$ = the risk evaluated with the effected system unavailability set equal to 1 (38)

$R(0)$ = the risk evaluated with the effected system unavailability set equal to 0. (39)

In evaluating the risk characteristics R(1) and R(0), all other variables not affected by the factor (i.e., other system unavailabilities, etc.) are set equal to their values characterizing the plant status.

Equation (37) says that the risk importance is simply a product of R(1) - R(0) and ΔQ. The quantity R(1) - R(0) is termed the Birnbaum importance and is the risk difference when the system is down versus when the system is up[6]. The quantity R(1) - R(0) has also been called the "maintenance impact" and "achievement worth"[5].

From Equation (37), it is seen that the Birnbaum importance R(1) - R(0) is not the actual risk importance and actual risk difference which is I(f). The actual risk importance I(f) is R(1) - R(0) multiplied by the change ΔQ in unavailability caused by the factor. Since ΔQ is less than 1, the quantity R(1) - R(0) is an upper bound on the actual risk importance I(f). However, this upper bound can be extremely conservative and may not be very meaningful in actual applications.

The critical input in determining the actual risk importance I(f) is asessing the size of change of system unavailability ΔQ caused by the factor. The size will be determined by considering the actual problem or application. If a value for ΔQ is not determinable, then meaningful bounds on ΔQ may be determinable. If some ΔQ is assumed, then the importance will be conditional on the assumed value. Sensitivity analyses may also be utilized to investigate the impacts of different ΔQ values.

The quantity R(1) - R(0) is straightforwardly determinable from available PRA's and does not involve any consideration of the effects of the factor. The quantity R(1) - R(0) can be expressed in alternate forms:

$$R(1) - R(0) = \Sigma C_i \tag{40}$$

and

$$R(1) - R(0) = \frac{dR}{d\overline{Q}} \tag{41}$$

Equation (40) expresses R(1) - R(0) as the sum of minimal cut set contributions whic contain the system unavailability with the unavailability set to 1. Equation (41) expresses R(1) - R(0) as the partial derivative of the risk function with respect to the system unavailability variable for the system affected. Which form is most useful will depend on how the PRA results are given. Usually Equation (40) is most straightforward for current PRA's which generally give minimal cut set contributions.

4.7.2 Multiple System Unavailabilities Affected by the Factor With no Interactions

The previous model can be straightforwardly generalized to a factor which affects multiple systems. Assume the effect of the factor changes several system unavailabilities, i.e., the factor has multiple system effects. Assume that N systems are affected and label the systems with indices from 1 to N. Assume the effect of the factor on system k is to change the unavailability from Q_k to Q_k where Q_k can either be greater or less than Q_k.

Assume also that each system unavailability appears as a linear term in the formula for the risk characteristic. Furthermore, assume that the effected system unavailabilities do not appear as a product anywhere in the formula for the risk characteristic. This latter assumption is a linear assumption and is valid if the effected sytems do not appear in the same accident sequence. Violations of this linear case are discussed later.

When the linear assumption is valid, using the general PRA formulas, the importance I(f) of the factor can be expressed as:

$$I(f) = (Q_1' - Q_1)\,(R_1(1) - R_1(0)) \tag{42}$$

$$+ (Q_2' - Q_2)\,(R_2(1) - R_2(0))$$

$$+$$

$$\cdot$$

$$\cdot$$

$$+ (Q_N' - Q_N)\,(R_N(1) - R_N(0))$$

where

$R_k(1)$ = the risk characteristic evaluated with the kth system unavailability set to 1 (43)

$R_k(0)$ = the risk characteristic evaluated with the kth system unavailability set to 0. (44)

In evaluating $R_k(1)$ and $R_k(0)$ the other risk variables are again set at values representing the plant status. In evaluating $R_k(1)$ and $R_k(0)$, any values can

be used for the other effected systems as long as they are the same in both $R_k(1)$ and $R_k(0)$. These other effected unavailabilities cancel out in the difference $R_k(1) - R_k(0)$.

Equation (42) says that the importance is simply the sum of the individual effects of the factor on each system unavailability. Each system effect is the change in system unavailability $Q_k' - Q_k$ multiplied by the Birnbaum importance $R_k(1) - R_k(0)$ of the particular system unavailability. Except for a possible sign change, each system effect is thus the importance of the factor on the individual system unavailability as given in the previous section.

As we have expressed it, the above formula for I(f) can either produce a negative value or positive value for the importance. If the value is positive, then the overall effect of the factor is detrimental. If the value is negative, then the overall effect of the factor is beneficial; we would simply reverse the sign in this case to have a positive importance.

As previously stated, the above linear equations will not apply if the effected system unavailabilities appear as a product in the expression for the risk characteristic. This will be the case when two or more effected systems appear in the same accident sequence. Equivalently, two or more affected systems will appear in the same accident minimal cut set. When the linear assumption does not hold, then it is best to simply use the general equation for the importance I(f):

$$I(f) = R(Q_1', Q_2' \ldots, Q_N') - R(Q_1, Q_2 \ldots, Q_N) \qquad (45)$$

where

$R(Q_1', Q_2' \ldots, Q_N')$ = the risk characteristic evaluated with the effected system unavailabilities set equal to $Q_1' \ldots, Q_N'$ (46)

and

$R(Q_1, Q_2 \ldots, Q_N)$ = the risk characteristic evaluated with the effected system unavailabilities set equal to $Q_1, Q_2 \ldots, ., Q_N$. (47)

All other variables in the risk expression are set equal to their plant status values.

4.7.3 One or More Component Unavailabilities Affected by the Factor with no Interactions

The previous system models can be directly applied to those cases where the factor affects one or more component unavailabilities. Assume the factor only affects one component unavailability and the unavailability appears as a linear term in the formula for the risk characteristic. Then the importance I(f) of the factor is given by

$$I(f) = (R(1) - R(0))\ \Delta q \qquad (48)$$

where

Δq = the change in the component unavailability caused by the factor (49)

and where now

R(1) = the risk characteristic evaluated with the effected component unavailability set equal to 1 (50)

R(0) = the risk characteristic evaluated with the effected component unavailability set equal to 0. (51)

From Equation (48) the importance of the factor I(f) is again simply the product of R(1) - R(0) multiplied by the change in component unavailability caused by the factor. The quantity (R(1) - R(0)) is the Birnbaum importance of the component unavailability. The above formula will apply if the risk characteristic is the core melt frequency, an accident sequence frequency, function unavailability, or system unavailability. The evaluation formulas for R(1) and R(0) given by Equations (40) and (41) also apply here where now the minimal cut sets are those containing the component unavailability and the derivative is with respect to the component unavailability.

When the factor affects multiple component unavailabilities with no interactions, then the overall importance I(f) is simply the sum of the individual component effects:

$$
\begin{aligned}
I(f) = & (q_1' - q_1)\ (R_1(1) - R_1(0)) \\
& + (q_2' - q_2)\ (R_2(1) - R_2(0)) \\
& + . \\
& \quad . \\
& \quad . \\
& + (q_N' - q_N)\ (R_N(1) - R_N(0))
\end{aligned} \tag{52}
$$

where

$$q_k' = \text{the final unavailability of the kth component} \tag{53}$$

and

$$q_k = \text{the initial unavailability of the kth component.} \tag{54}$$

For the above, as in the preceding section, the factor changes the component unavailability from q_k to q_k'.

When two or more component unavailabilities appear as a product in the risk expression, the above linear equations will again not apply. This will occur when two or more of the effected components occur in the same minimal cut set. When the linear assumption does not hold, then again it is usually most straightforward to use the general equation for the importance I(f):

$$I(f) = R(q_1', q_2' \ldots, q_N') - R\ (q_1, q_2 \ldots, q_N) \tag{55}$$

where

$R(q_1', q_2' \cdots, q_N')$ = the risk characteristic evaluated with the effected component unavailabilities set equal to $q_1', q_2' \cdots, q_N$ (56)

and

$R(q_1, q_2, \ldots, q_N)$ = the risk characteristic evaluated with the effected component unavailabilities set equal to $q_1, q_2, \ldots, q_N$. (57)

4.7.4 Local Changes Caused by the Factor

An important class of models is where the factor causes a small local change in one or more of the risk variables. The risk variables affected by the factor can be system or component unavailabilities, but can also be component failure rates, human error rates or any other risk variables. When the factor causes a small local change in the risk variable, then the risk variable only varies in a small manner from a reference starting value, i.e., the risk variable is perturbed from its reference, starting value.

When perturbations occur in the risk variables, then the change in the risk characteristic can be adequately approximated by first order linear terms involving the changes in the risk variable. For example, if the variable is a component unavailability q then a small local change Δq in the component unavailability means that the risk difference can be accurately expressed as a function of Δq only and not $(\Delta q)^2$, $(\Delta q)^3$, etc. Even if there are interactions, when the change in the risk variable is small, then the terms involving products of the variable changes ($(\Delta q)^2$ etc.) will be small compared to the terms involving only the risk variable change itself.

We will thus define perturbations in the risk variable to mean changes such that the risk difference can be adequately approximated by first order terms. This is the standard definition of local changes or perturbations in perturbation theory and we are simply applying the concept to the calculation of importances. We will call the models which determine the importance of a factor which causes local changes or perturbations in the risk variable, local importance models.

Local importance models are applicable when the objective is to identify importances of factors which can cause perturbations from the present situation. The local importances of factors will identify those factors which should be focused upon because of their significant perturbation effects. Local importance models can also be useful in providing first order screenings of factors which can have larger impacts.

The equations for calculating the local importance of any factor can be developed in a straightforward manner using perturbation theory approaches.

Assume a factor f causes local changes in the risk variables $x_1, x_2, \ldots x_N$ where the variables can be of any type and any number N can be mutually affected by the factor. We can symbolize the factor's local effects by the expression:

$$f \Rightarrow \Delta x_1, \Delta x_2, \ldots, \Delta x_N \tag{58}$$

where the symbol "$\Rightarrow$" stands for the word "causes" and $\Delta x_1, \Delta x_2 \ldots \Delta x_N$ are the local changes in the specific variables affected. The above expression thus simply says that f causes $\Delta x_1, \Delta x_2, \ldots, \Delta x_N$. The changes in the variables are measured as the perturbed final value minus the initial value.

Because the risk variable changes are local perturbations, the risk difference ΔR can be expressed as

$$\Delta R = C_1 \Delta x_1 + C_2 \Delta x_2 + \ldots + C_1 \Delta x_N \tag{59}$$

where the C_1's are constants. The risk difference is thus a linear function of the risk variable changes. The risk difference is again measured as the perturbed final risk value minus the initial risk value.

We will assume the risk difference ΔR is positive. In this case, the importance of the factor I(f) is simply equal to the risk change

$$I(f) = \Delta R \tag{60}$$

We will use the above equation in the following. If the risk difference is actually negative, then we will obtain a negative value for the importance and we will simply have to change the sign.*

---

* We could have expressed I(f) more generally as the absolute value ΔR . The above convention avoids having to use the absolute value symbol.

Substituting Equation (59) into (60), we thus have

$$I(f) = C_1 \Delta x_1 + C_2 \Delta x_2 + \ldots + C_N \Delta x_N \tag{61}$$

and the local importance is the same linear function of the risk variable changes as the risk difference is. To determine the constants C_i we can refer to standard expansion approaches, or to calculus, to obtain

$$C_k = \frac{dR}{dx_k} \quad , k = 1,\ldots,N \tag{62}$$

where the term on the right hand side is the partial derivation of the risk function with regard to the risk variable x_k. Using Equation (62) we thus have the following final formula for the local importance I(f)

$$I(f) = \frac{dR}{dx_1}\cdot\Delta x_1 + \frac{dR}{dx_2}\cdot\Delta x_2 + \ldots + \frac{dR}{dx_N}\cdot\Delta x_N \tag{63}$$

To be able to apply Equation (63), we need to be able to determine the derivatives $\frac{dR}{dx_k}$ and the perturbation sizes Δx_k. The derivatives are straightforward to obtain if the equation for the risk in terms of the variables is available which it generally is. If it is not, the derivatives can be approximated by the ratios of the small differences as is standardly done. The examples in the next section demonstrate how the derivatives can be obtained for a variety of cases.

The sizes of the perturbations Δx_k can be determined in various ways. One straightforward approach is to assess the perturbation sizes with regard to some reference value Δs:

$$\frac{\Delta x_k}{\Delta s} = r_k \quad . \tag{64}$$

Using Equation (64), we can then express the local importance as

$$I(f) = \left(\frac{dR}{dx_1}\cdot r_1 + \frac{dR}{dx_2}\cdot r_2 + \ldots + \frac{dR}{dx_N}\cdot r_N\right) \Delta s \tag{65}$$

In ranking the relative importances of different factors, the reference perturbation Δs will cancel out if the same reference perturbation is used for the different factors. (We can easily see this since if we take the ratios of two different importances $I(f)$, the Δs will cancel out if it is the same.) Consequently, if all perturbations are measured on the same scale, we will need to know only the relative values r_k of the perturbations and not their absolute values $r_k \cdot \Delta s$.

We can re-express Equation (65) in the form

$$\frac{I(f)}{\Delta s} = \frac{dR}{dx_1} \cdot r_1 + \frac{dR}{dx_2} \cdot r_2 + \ldots + \frac{dR}{dx_N} \cdot r_N \quad . \tag{66}$$

We can call the ratio $I(f)/\Delta s$ the normalized, local importance since we are normalizing by the reference perturbation Δs. The normalized importance is nothing more than the normalized change in the risk characteristic $\Delta R/\Delta s$:

$$\frac{I(f)}{\Delta s} = \frac{\Delta R}{\Delta s} \tag{67}$$

The normalized local importance is a generalization of the directional derivative standardly treated in calculus ("directional" here indicating that the variables Δx_k have different relative changes).

For ease of notation we will denote the normalized, local importance by $i(f)$:

$$i(f) = \frac{I(f)}{\Delta s} \tag{68}$$

Then we have

$$i(f) = \frac{dR}{dx_1} \cdot r_1 + \frac{dR}{dx_2} \cdot r_2 + \ldots + \frac{dR}{dx_N} \cdot r_N \tag{69}$$

The normalized, local importance can be a useful measure for relatively ranking the importances of different factors. The ratios of the normalized local importances of different factors will give the relative rankings of the factors with regard to their perturbations on the risk characteristic. The subsequent examples will illustrate some of the uses of i(f). As will be seen, in certain cases i(f) equals the Birnbaum importance or a weighted Birnbaum importance.

To conclude this section, we summarize the general steps which need to be taken to use a local importance model:

1. Validate that perturbations caused by the factor are applicable for determining the importance.
2. Determine the affected variables x_1, x_2,...x_N which are perturbed by the factor and whose perturbations can be meaningfully assessed, at least relatively.
3. Obtain the risk characteristic as a function of the variables. This is generally obtainable from PRA's or reliability analyses.
4. Determine the derivatives of the risk characteristic with regard to the affected variables.
5. Assess the sizes of the perturbations of the affected variables. If relative rankings of importances are only to be obtained, then the relative sizes of the perturbations need only be determined.
6. Calculate the local importance of the factor using Equation (63) or the normalized, local importance using Equation (69).

4.8 Example Applications of Specific Models

This section gives example applications of the specialized models which were discussed in the preceding section. The examples include applications of local importance models and applications of more global importance models where the changes in the risk variables are not limited to perturbations.

4.8.1 Importance of a Degrading Environment

Assume there is a degrading environment which causes the component unavailability to deviate from its nominal, or designed, value. The deviation is a perturbation in that there is a degradation in component performance but not a significant loss of the component's function capability. Examples of such degrading environments are dirtier than normal environments for diesels and above normal impurities in water supply sources for feedwater systems.

The degrading environmental factor causes a degradation, or perturbation, Δq in the component's unavailability. This in turn causes an increase ΔR in the risk where

$$\Delta R = \frac{dR}{dq} \Delta q \tag{70}$$

The importance I(f) of the degrading environment is equal to ΔR and hence is equal to

$$I(f) = \frac{dR}{dq} \Delta q \tag{71}$$

The derivative dR/dq is another form of the Birnbaum importance which is obtainable from PRA's as the last section described. If Δq can be estimated, then Equation (71) can be used to calculate the importance. To account for the likelihood of the deviation existing, Δq can be expressed as $p\Delta q'$ where p is the likelihood of the degrading environment existing and

$\Delta q'$ is the unavailability change given the degrading environment exists*. If Δq cannot be directly assessed, then Δq has to be related to more basic variables which can be estimated or be measured. In subsequent examples we shall further address the assessment of Δq.

4.8.2 Ranking Several Degrading Environments

Assume the goal is to rank the importance of several possible degrading environments as to their risk importance. This can be useful in deciding where to focus inspection and quality control efforts. Assume that each degrading environment will affect a different component. Label the environments such that environment k affects component k. Using the results of the previous example, the importance I(k) of degrading environment k is then

$$I(k) = \frac{dR}{dq_k} \Delta q_k \tag{72}$$

Assume now that it is postulated that the different degrading environments are such as to cause an equal increase in the different component unavailabilities:

$$\Delta q_k = \text{is the same for all environments } k \tag{73}$$

The Δq_k's will then cancel out in taking the ratios of I(k) for different environments. Therefore the normalized local importances $I(k)/\Delta q_k$ can be used to relatively rank the importances of the different degrading environments:

$$\frac{I(k)}{\Delta q_k} = \frac{dR}{dq_k} \tag{74}$$

Consequently the environments can be ranked by simply calculating and ranking the Birnbaum importances of the different components affected by the environments.

---

* Note for the perturbation approaches to be valid Δq only need be relatively small. The change $\Delta q'$ can thus be large as long as p is small so as to make the expected value $p\Delta q'$ small.

Assume now however that it is postulated that the degrading environments are such as to cause an equal fractional change in the unavailabilities:

$$\frac{\Delta q_k}{q_k} \text{ is the same for all environments k} \tag{75}$$

The importance of environment k then can be re-expressed as

$$I(k) = \frac{dR}{dq_k} \; q_k \; \frac{\Delta q_k}{q_k} \tag{76}$$

Because $\Delta q_k/q_k$ cancel out in taking ratios, the environments can be relatively ranked by calculating the normalized importance $I(k)/(\Delta q_k/q_k)$,

$$\frac{I(k)}{\frac{\Delta q_k}{q_k}} = \frac{dR}{dq_k} \; q_k \tag{77}$$

The importance of the environmental factors can thus now be ranked by calculating the Birnbaum importance times the unavailability for each affected component. This ranking can be quite different from the previous ranking of the environments based on the assumption of equal Δq and using only the Birnbaum importances. Thus the assumption of the type of effects the environments have on the component unavailabilities (e.g., the same Δq or the same $\Delta q/q$) significantly impacts the final rankings obtained for the importance of the environments. This is true not only for environmental factors, but for any factor.

In general, to obtain the correct environment importance rankings, the expected relative effects on the component unavailabilities, i.e., the Δq's, need to be correctly assessed. As was discussed previously, this can be done in several ways. A straightforward way is to use one of the unavailability effects, say Δq_1, as a reference. The other unavailability effects are then compared to it:

$$\frac{\Delta q_k}{\Delta q_1} = r_k \tag{78}$$

where r_k is the relative unavailability effect on component k compared to the unavailability effect on component 1.

The relative ratings r_k of the unavailability effects can take into account the relative likelihoods of the different environments as well as the different impacts given the environments. For example, expressing Δq_k as

$$\Delta q_k = P_k \, \Delta q_k' \tag{79}$$

where

$$P_k = \text{the likelihood of degrading environment } k \tag{80}$$

and

$$\Delta q_k' = \text{the unavailability change given the environment} \tag{81}$$

then

$$r_k = \frac{P_k}{P_1} \cdot \frac{\Delta q_k'}{\Delta q_1'} \tag{82}$$

Using the relative comparisons r_k, given by Equation (78) or (82) the importance I(k) of environment k can then be expressed as

$$I(k) = \frac{dR}{dq_k} \cdot r_k \, \Delta q_1 \tag{83}$$

Since all the importances now have a common reference point Δq_1, it cancels in taking ratios of I(k). We can therefore use the normalized importances $I(k)/\Delta q_1$ to relatively rank the environments:

$$\frac{I(k)}{\Delta q_1} = \frac{dR}{dq_k} \cdot r_k \tag{84}$$

Thus, in general, the correct ranking of the environmental importance is obtained by calculating the Birnbaum importance times the relative size of the expected environment effect on the component unavailability.

4.8.3 Importance of Deviations in Scheduled Test Times

This example shows how we can relate Δq to more basic variables. Assume for this example that a component is supposed to be tested at an interval no greater than T. We want to examine the importance of deviations from this interval, in particular deviations which result in test intervals greater than T. Tests where deviations are of relatively high risk importance can be focused upon in inspecting whether tests are performed on schedule.

A deviation ΔT in the test interval T will cause a deviation Δq in the component unavailability q. The risk increase ΔR is then

$$\Delta R = \frac{dR}{dq} \Delta q \tag{85}$$

This is also the importance of the test interval deviation ΔT; we shall denote the importance by $I(\Delta T)$. Hence

$$I(\Delta T) = \frac{dR}{dq} \Delta q \tag{86}$$

We need now to relate Δq to the test interval deviation ΔT. We can do this by using the appropriate formula for q in terms of T. These are standard formulas in PRA's and the applicable formula depends upon the type of component and test. For this example, we shall use the formula

$$q = \frac{1}{2} \lambda T \tag{87}$$

where λ is the component failure rate.* Taking the differential of Equation (87) we obtain

* To apply this formula, the component test downtime should be negligible and the failure rate be entirely time related.

$$\Delta q = \frac{1}{2} \lambda \Delta T \quad (88)$$

Hence Equation (86) becomes

$$I(\Delta T) = \frac{dR}{dq} \frac{1}{2} \lambda \Delta T. \quad (89)$$

We can now use Equation (89) to calculate the risk increase, which is the importance $I(\Delta T)$, for specific test deviations. We can also use Equation (89) to relatively rank the importances of test interval deviations for different tests. If we rank the importances for equal test deviations, the test deviation ΔT will cancel in the ratios of the importances. Hence we can use the normalized importances $I(\Delta T)/\Delta T$ to rank the importances of different test interval deviations:

$$\frac{I(\Delta T)}{\Delta T} = \frac{dR}{dq} \frac{1}{2} \lambda \quad (90)$$

Because Equation (87) is linear in T, the above formulas for $I(\Delta T)$ and $I(\Delta T)/\Delta T$ are valid for any size of ΔT and not only for relatively small perturbations. For equations for q which are not linear in T, this generality will not hold. For these nonlinear cases, the risk importance for any size ΔT can be straightforwardly determined using the general expression for the importance $I(\Delta T)$:

$$I(\Delta T) = R\ (T+\Delta T) - R(T) \quad (91)$$

where $R(T+\Delta T)$ is the risk with test interval $T+\Delta T$ and $R(T)$ is the risk with test interval T.

4.8.4 Importance of Aging

In the very first example, environmental degradations were considered which caused an increase Δq in the component unavailability. The expression for the importance $I(f)$ of the environmental degradation was given as

$$I(f) = \frac{dR}{dq} \Delta q\ . \quad (92)$$

As was previously stated if Δq cannot be assessed directly then it needs to be related to more basic variables.

As a specific example of more basic evaluations, consider the degradation caused by aging. Aging can be caused by various mechanisms such as bearing wear or contamination build-up. A straightforward model of aging is to model the aging as causing a linear increase in time in the failure occurrence rate. If there were no aging, the failure occurrence rate w is a constant λ as is standardly modeled in PRA's:

$$w = \lambda : \text{ no aging ,} \tag{93}$$

where λ is the exponential failure rate used in PRA's.

When aging causes the failure occurrence rate to linearly increase with time, then w is given by

$$w = \lambda + bt \tag{94}$$

where t is the operating or standby time and b is the rate of increase of the failure rate w. The aging rate b can be expressed in terms of more basic root causes such as the contamination buildup rate or the bearing wear-rate and the susceptibility of the component to the contamination or deformation. The model given by Equation (94) is thus applicable when there is a linear buildup in the general stress which causes the aging. When b is small, the above formula is generally applicable for <u>any</u> aging degradations since any general expression for w can then be adequately approximated by its linear term.

Using the above linear model for w, the component unavailability q at some detection or test time T is then

$$q = 1 - \exp\left(-\int_0^T (\lambda+bt)dt\right) \tag{95}$$

where "exp" denotes the exponential and "$\int$" is the integral symbol.

We shall approximate the exponential by its first order term and hence

$$q = \lambda T + \frac{bT^2}{2} \tag{96}$$

The above formula is accurate if q is less than 0.1. The average unavailability $\bar{q}$ over the time period T is similarly

$$\bar{q} = \frac{1}{2} \lambda T + \frac{1}{6} bT^2 \tag{97}$$

As stated we need an expression for Δq in order to compute the aging importance given by Equation (92). For Δq due to aging occurring, we shall use the difference in the average unavailability $\bar{q}$ when there is aging and when there is no aging. When there is no aging $\bar{q} = \frac{1}{2} \lambda T$. Hence using Equation (97) for the aging case, we have

$$\Delta q = \frac{1}{6} bT^2 \quad . \tag{98}$$

The importance of the aging of the component I(f) is then finally

$$I(f) = \frac{dR}{dq} \frac{1}{6} bT^2 \tag{99}$$

As seen from Equation (99) the aging importance is a strong function of the detection period T. The period T is the time in which the aging can occur before detection. For aging which is not detectable then T can be taken as the remaining lifetime of the plant.

Equation (99) can be now used to evaluate the importance for specific rates of aging b. The aging rate can be estimated from data or can be assessed from engineering considerations of the aging mechanisms. Relative importances of aging of different components can also be evaluated. For equal aging rates for the components, the values b cancel out in calculating the relative importances (the ratio of importances). As stated, simple formulas can furthermore be used to explicitly relate b to root cause variables and mechanisms for which engineering assessments can oftentimes be more readily made.

4.8.5 The Birnbaum Importance

Assume for this application we want to calculate the importance of a component failing or of being down. This importance is useful for example for prioritizing corrective maintenance activities. Consider the importance of a component failure. When a component fails it goes from an up state to a down state. Thus, the importance of the component failure I(f) is

$$I(f) = R(1) - R(0) \tag{100}$$

$$= \frac{dR}{dq}, \tag{101}$$

where R(1) is the risk with the component down and R(0) with the component up. The importance is simply the Birnbaum importance.

The importance of a component being down is the same as the importance of the component failing if the importance is measured with regard to the component being up:

$$I(f) = \text{the importance of the component being down as compared to when it is up} \tag{102}$$

$$= R(1) - R(0) \tag{103}$$

If the importance of the component being down however is measured with regard to its expected operational state, then the importance I(f) is:

$$I(f) = \text{the importance of the component being down as compared to its expected operational state} \tag{104}$$

and

$$I(f) = R(1) - R \tag{105}$$

The risk R is the usual risk calculated in PRA's with an average component unavailability q used for the component of interest. For the importances

given by Equation (104) we have no knowledge of the component's state before finding it failed.

The importance given by Equation (105) is not the Birnbaum importance but will often be essentially equal to it in numerical value. In particular, for components which have significant risk impacts, there will be minor differences between the two importances calculated by Equation (103) and (105). This is due to the fact that for important components R(1) is significantly larger than either R(0) or R; hence, both importances are essentially equal to R(1) and the Birnbaum importance can be used. For components which have lesser risk impacts, there will be differences in the importance values; which value is applicable will depend upon the information known about the component before the component is down. Since both importances will be small, the differences in these cases will generally not be pertinent.

One important point should be noted about the above importances and in particular the Birnbaum importance which is often used. The Birnbaum importance assumes the component is down and is the impact of this assumed failed state relative to being up or relative to the expected operational state. We can thus characterize the Birnbaum importance as being a conditional importance assuming or given a failed state. Hence, the Birnbaum importance is applicable in prioritizing actions knowing the component is down. Such actions include determining the amount of allowed downtime to allot for repair after the component failure has been detected and determining the importance of corrective activities which are carried out after the failure is discovered.

The same restrictions on the applicability of the Birnbaum importance also apply to the risk achievement worth as defined in (4) since it simply is the same measure, but on a ratio scale.

4.8.6 The Fussell-Vesely Importance

From the previous example, the risk importance of a component which is assumed to fail is the Birnbaum importance R(1) - R(0). This is also the importance of a component (or system) which is assumed to be down where the

importance is measured with regard to the up state. To account for the likelihood that the component actually does fail or is actually down the Birnbaum importance needs to be multiplied by the appropriate probability.

Let I(f) be the importance of a failure occurring which includes the likelihood of failure occurrence:

$$I(f) = \text{the importance of a failure including its likelihood of occurrence.} \quad (106)$$

Then

$$I(f) = (R(1) - R(0))\, w \quad (107)$$

where

$$w = \text{the component failure occurrence rate} \quad (108)$$

For a constant occurrence rate, w is the same as the exponential failure rate standardly used in PRA's. The importance in Equation (107) can be termed the <u>expected importance</u> since the failure impact R(1) - R(0) is multiplied by the likelihood or frequency of the failure actually occurring.

For the importance of a component being down, let I(f) now be the importance of a component being down which includes the likelihood of actually being down:

$$I(f) = \text{the importance of a component being down including its likelihood of being down} \quad (109)$$

Then

$$I(f) = (R(1) - R(0))q \quad (110)$$

where

$$q = \text{the probability of the component being down (the component unavailability)} \quad (111)$$

The component unavailability q is the unavailability standardly computed in PRA's. The component unavailability accounts for not only the component failure rate λ but also the time during which the failure exists. (For example, a simple expression for q for failures occurring between tests is $q = 1/2 \lambda T$ where T is the test interval.) More detailed expressions account for other contributions. As in the previous paragraph, the above importance given by Equation (110) can be termed an <u>expected importance</u> since the impact of being down R(1) - R(0) is multiplied by the probability of actually being down q.

The above importances are sometimes called Fussell-Vesely importances[7]. The Fussell-Vesely importance is usually associated with the importance of being down (Equation (110)), however Equation (107) is the same type of importance applied to failure occurrences. The Fussell-Vesely importance is also usually divided by the sum of all the component importances (all the contributions) however, this is simply a normalization. The above importances, the Fussell-Vesely importances, are simply the contributions of the components to the total system failure frequency or total system unavailability.

From the above it is seen that the Fussell-Vesely importances are quite different from the Birnbaum importances as to where they're applicable. The Birnbaum importance assumes the component fails or is down. Because the Fussell-Vesely importance includes the likelihood of the component failing or being down, it is applicable for determining risk importances when the component is <u>not known</u> to be failed or be down. The Fussell-Vesely importances of are useful, for example, in helping to prioritize where <u>inspections</u> should be carried out to determine <u>if</u> failures have occurred or <u>if</u> components are down. Fussell-Vesely importances are therefore useful in the general areas of failure inspection and preventative maintenance while Birnbaum importances are useful in the general areas of failure repair and corrective maintenance. How these importances are specifically used in these areas and what else needs to be incorporated, if anything, will of course depend upon the specific problem.

4.8.7 Importance of a Pre-Operational Test

Consider again the example of calculating the importance of a pre-operational test. For our specific example, we will evaluate a pre-operational, (pre-op) test which can be performed on a component. If the pre-op test is performed, the component will be tested and observed and will be repaired if it is found to be inoperable. We will consider repair which restores the component to its normal state as modeled in the PRA. This normal state includes failure possibilities which may be inherent to the component or which may occur in subsequent operation. The repair does not restore the component to as good as new but only corrects failures associated with installation and start-up (design errors, manufacturing errors, etc.). It is important to define these considerations since they can impact the importance determinations.

To determine the importance of the pre-op test we need to evaluate the risk with and without the pre-op test. Let

$$R\ (\text{with test}) = \text{the risk if the test is performed} \qquad (112)$$

$$R\ (\text{without test}) = \text{the risk if the test is not performed} \qquad (113)$$

The importance of the test I(test) is the difference in the risk, or the risk reduction resulting from the test:

$$I(\text{test}) = R(\text{without test}) - R(\text{with test}) \qquad (114)$$

Consider first the risk with the test R(with test). When the test is performed it restores the component to a normal state if a failure is detected. If a failure is not detected, then the component will remain in the normal state. Thus in either case

$$R(\text{with test}) = R \qquad (115)$$

where

$$R = \text{the normal steady state risk as modeled in PRA's} \tag{116}$$

Note we are only considering the one component as having possible installation or start-up failures.

Consider now the risk without the pre-op test R(without test). If there is an installation failure, the risk will be R(1) which is the risk with the component down. The likelihood of having an installation failure is assessed to be p. If there is no installation error, the risk is the normal risk R; the likelihood of this occurring is 1-p. The expected risk without the pre-op test is thus

$$R(\text{without test}) = pR(1) + (1-p)R \tag{117}$$

The importance of the pre-op test is consequently

$$I(\text{test}) = R(\text{without test}) - R(\text{with test}) \tag{118}$$

$$= pR(1) + (1-p)R - R \tag{119}$$

or

$$I(\text{test}) = p(R(1) - R) \tag{120}$$

This is similar to a Fussell-Vesely importance with the modification that the probability of an installation error p is used instead of the standby unavailability q usually calculated in PRA's and the base risk R is used instead of R(0). (We would have R(0) instead of R if we assumed the pre-op test restored the component to as good as new. The impact of this particular modification on the importance calculation is however generally small as previously discussed.)

The above analyses can be straightforwardly extended in various ways. If we want to explicitly include the downtime d during which the installation error would exist before discovery, then we would change p to an unavailability pd and have

$$I(\text{test}) = pd\,(R(1) - R) \tag{121}$$

The inclusion of d would be important in comparing the importances of different pre-op tests which could have different associated downtimes before the failures were detected.

As another extension, different pre-op test alternatives could be evaluated for their risk impacts, or importances, by defining the specific tests that would and would not be carried out (or be observed) for each alternative. We could then evaluate the expected risk reduction that would result if a particular alternative were carried out. The risk impact would be dependent upon the particular set of pre-op tests carried out. This impact would not in general simply be the sum of the individual test impacts because of the interaction effects among the different tests.* The alternative with the lowest risk would be the best strategy in reducing the risk and would have the greatest importance.

To actually calculate the risk importance, order of magnitude assessments are often sufficient for actual implementations. Also relative values are only required for ranking different importances. For example, in comparing the risk importances or impacts of two pre-op tests, say pre-op test 1 and pre-op test 2, the ratios of importances would be:

$$\frac{I(\text{test } 1)}{I(\text{test } 2)} = \frac{p_1}{p_2} \cdot \frac{d_1}{d_2} \cdot \frac{(R_1(1)-R)}{(R_2(1)-R)} \quad . \tag{122}$$

Thus, only the relative likelihood p_1/p_2 of the different installation failures existing and only the relative downtimes d_1/d_2 would need to be assessed. The risk difference $R_1(1) - R$ with component 1 down and $R_2(1) - R$ with component 2 down are straightforwardly determined from PRA's or reliability models. The above evaluations are thus doable.

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* The set of tests having the greatest risk impact would be the set providing the greatest integral assurance associated with the success paths (see Section 3.4). The degree of integral assurance would now be quantified by the importance.

4.8.8 Importance of a Corrective Maintenance

We explicitly show here that the Birnbaum importance is a measure of the importance of a corrective maintenance. We also discuss considerations which are involved in obtaining other, more detailed measures of the importances of corrective maintenance. Finally, we will describe ways the importance measures can actually be implemented.

Assume a component is down and we want to measure the importance of a corrective maintenance which is about to be performed on the component.

Let

$$I(cm) = \text{the importance of a corrective maintenance to be performed on a given, downed component} \quad (123)$$

We define I(cm) to be

$$I(cm) = \text{the risk without the corrective maintenance} - \text{the risk with the corrective maintenance} \quad (124)$$

Consider the risk with the corrective maintenance. We assume the corrective maintenance is effective and brings the component back up. Hence

$$\text{the risk with the corrective maintenance} = R(0), \quad (125)$$

where R(0) is the risk evaluated with the component up (the unavailability set equal to zero).

If the corrective maintenance is not performed, then the component will remain down. Hence, the risk without the corrective maintenance is R(1), the risk with the component down (the unavailability set equal to 1):

$$\text{the risk without the corrective maintenance} = R(1) \quad (126)$$

Note that if the corrective maintenance were completely ineffective so that the component remains failed, then the risk would also be R(1).

Substituting Equation (125) and Equation (126) into Equation (124), we have for the importance of the corrective maintenance:

$$I(cm) = R(1) - R(0) \tag{127}$$

which is simply the Birnbaum importance. The Birnbaum importance thus gives the reduction in r⁽ᐧ⁾ in effective repair of a failed component.

There are some points that should be noted about Equation (127). First, as was indicated, Equation (127) also measures the impact of completely effective versus completely ineffective maintenance:

$$\text{the risk impact of completely effective versus completely ineffective maintenance} = R(1) - R(0) \tag{128}$$

If this risk impact is large, then it is especially important that assurance is taken that the maintenance is effective. This can be done by inspector observation, quality control procedures, and/or maintenance personnel training associated with this particular corrective maintenance.

The second point is that Equation (127) measures only the impact of an effective (or ineffective) maintenance and does not consider impacts of partially effective maintenance. Possible deteriorations in maintenance which leave the component in a degraded but operable state are not treated by Equation (127). The perturbation approaches treating increases Δq in the unavailability, which were previously discussed, are applicable for these deterioration considerations. Note however that the risk impact of a deterioration in maintenance will be smaller than the risk impact of a completely ineffective versus effective maintenance given by Equation (127). Hence, if Equation (127) gives small risk impacts then deteriorations will give still smaller risk impacts.

The third point is that reconfiguration of components may or may not be incorporated in the calculations of Equations (127) or (128). This has to

be explicitly identified. When a component is down for corrective maintenance other components may be reconfigured to account for the component's being down. The reconfiguration of components is treated in the calculation of R(1) and is part of the plant status definition. Generally, if reconfiguration is not taken into account, then R(1) will be larger than if it were taken into account. Not treating reconfigurations can thus serve as bounding calculations since the importances of any corrective maintenances with reconfigurations will be larger than actual.

The fourth point is that the Birnbaum importance computed in Equation (127) does not consider the time period during which the component will remain down if the maintenance is not performed or is ineffective. These downtime considerations are important if different components have significantly different downtimes until the ineffectively maintained components are detected and finally restored to an up condition. If d is the downtime until effective restoration, then using integral risk considerations the importance I(cm) can be modified to be

$$I(cm) = (R(1) - R(0))d \tag{129}$$

For d equal to the allowed outage time (AOT) given by the plant technical specifications (tech specs), Equation (129) gives the importance of the corrective maintenance effectively restoring the component in the allowed outage time.

Finally, and this deserves repeating, because all the previous corrective maintenance importances are based on the assumption that the component is known to be down, they are applicable in the situation where this knowledge exists. The importances are applicable for helping the inspector or plant personnel decide whether a corrective maintenance about to be performed should be observed and be quality controlled. These importances are also useful in helping to focus where repair procedures need to be examined for their effectiveness and where maintenance personnel need to be trained. If the importances of effective corrective maintenances are high, then it is important that procedures be effective and plant personnel be trained in these

corrective maintenances to ensure that the important corrective maintenances are indeed effective.

There are various ways the corrective maintenance importances can actually be implemented. Equation (127) gives the risk increase during the corrective maintenance. If this is above a specified critical value, such as the safety goal value, then it can be deemed to be important that the maintenance be assured to be effective. These important maintenances can be specially tagged for inspection or reliability assurance focus. If Equation (129) incorporating the allowed downtime is used then, in a similar manner, some criterion on the integral risk can be established to denote important maintenances; for example, the safety goal value can be translated to be an integral risk criterion with which to compare Equation (129) to identify important maintenances.

If Equation (129) incorporating the downtime is used, then it is important to also examine the cumulative risk impact coming from the cumulative number of maintenances performed:

$$I(cm) = \text{the cumulative importance of the corrective maintenance} \quad (130)$$

$$= N\, d\, (R(1) - R(0)) \quad (131)$$

where N is the expected number of maintenances in a time period such as a year.

Equation (131) gives the added perspective that a corrective maintenance may have large cumulative risk impacts and be important because it is performed frequently (have a large N). A criterion can again be defined to identify corrective maintenances which have significant I(cm); this criterion for example can again be the safety goal translated as an integral risk criterion.

Instead of using absolute criteria, the importances can be simply ranked in a relative manner from highest to lowest. The corrective maintenances can be categorized into classes according to their risk importance, giving "Class 1 maintenances", "Class 2 maintenances", etc. The absolute importances (the actual risk differences) and the associated absolute

criteria have the advantage over the relative rankings in that they give the actual risk impact and actual importance of the corrective maintenance. However, the relative rankings provide an important prioritization of the maintenances which can be used to focus activities and programs.

In general, the Birnbaum importance given by Equation (127) will give the largest risk difference and largest importances. The Birnbaum importance can thus be used as the bounding importance evaluation. The other modified importances given by Equations (129) and (131) can be used in more comprehensive implementations. For example, a corrective maintenance can be deemed important if any of the three importance measures are significantly high (above defined criteria). In terms of relative rankings, the Birnbaum importance can be used as a bounding ranking or the relative ranks of the three importance measures can be combined. For example the maximum rank can be used (this will give ties in the ranks but this is generally not a problem). The importances can thus provide very useful information for implementation purposes.

4.8.9 Importance of a Surveillance Test

In this final example, we explicitly derive the importance of a surveillance test and show that the importance is the Fussell-Vesely importance. We also discuss more detailed test considerations and describe implementations of the importance measures.

Assume a periodic, surveillance test is performed on a standby component* at intervals of T. We wish to measure the risk importance of the surveillance test. Let

I(st) = the importance of a surveillance test which is performed on the given component (132)

We define I(st) to be:

I(st) = the risk without the surveillance test - The risk with the surveillance test (133)

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* The component can also be a subsystem or train of a system.

Consider the risk with the surveillance test. We consider the risk immediately after the test is performed. Assuming the surveillance test is effective, if the component is found failed, it is brought back up. Hence the risk with the test is R(0), the risk with the component up:

$$\text{the risk with the surveillance test} = R(0) \tag{134}$$

Consider the risk without the test. We again consider the risk immediately after the test (if it had been performed). If the component is up, then the risk is R(0); the probability of this occurring is 1-q where q is the unavailability of the component (the probability of being down). If the component is down, then the risk is R(1); the probability of this occurring is q. Hence

$$\text{the risk without the surveillance test} = (1-q)\, R(0) + qR(1) \tag{135}$$

Substituting Equations (134) and (135) into Equation (133), the importance of the surveillance test I(st) is then:

$$I(st) = (1-q)\, R(0) + q\, R(1) - R(0) \tag{136}$$

or

$$I(st) = q\, (R(1) - R(0)) \tag{137}$$

which is the Fussell-Vesely importance.

Some important points should be noted about Equation (137). First of all, Equation (137) measures the importance of one surveillance test at a given time being performed on the component. The importance is measured in the context of all the other surveillance tests being performed on the component. The importance of N surveillance tests performed on the component can be taken as approximately N times the Fussell-Vesely importance provided the unavailability linearly increases with the test interval. This will be true for the component having a constant failure rate (per unit time) and for q .1 (which are usual PRA models).

The component unavailability q which is used in Equation (137) is the unavailability due to latent failures occurring between the tests. This is the unavailability due to the per hour failure rate contribution. The per cycle failure rate contribution should ideally not be included since this contribution remains constant with and without the test. If the total unavailability is used in Equation (137), including both the per hour and per demand contributions, then the importance will be biased high.

Let us define a completely ineffective test to be one which is not able to detect any failures and is the same as doing no test at all. Then Equation (137) also gives the risk impact of performing an effective test versus performing a completely ineffective test:

$$\text{the risk impact of an effective versus completely ineffective test} = q\,(R(1)-R(0)) \qquad (138)$$

If the risk impact, or importance, is large, then it is important that assurance be taken that the test is indeed effective. This means assuring that the test is able to detect the critical failure modes in the PRA, that the test is recorded and done efficiently, and that the test have no deleterious effects.

Equation (137) gives the risk reduction of performing a surveillance test, and hence Equation (137) can be viewed as giving the risk benefits of one surveillance test. This quantification of the risk benefits of one surveillance test can be useful for cost-benefit types of evaluations where benefits versus cost of a test are compared.

Equation (137) does not take into account partially effective tests or deleterious tests which actually can increase the component unavailability. The impact of an ineffective test is to decrease the detectable unavailability q, where only restricted failure modes are now detectable, and to change R(0) to some higher value $R(q_r)$ where q_r is the residual undetectable unavailability after the test. Both these effects will decrease the importance of the test as calculated by Equation 137). If the test has low importance using Equation (137) where it is treated as being effective, then

it will have even lower importance when inefficiencies are considered. The inefficiencies can be modeled if deemed necessary, for example, for sensitivity studies.

The impact of a deleterious test is to raise the unavailability after the test to a higher value than before the test. Thus, if q is the unavailability before the test, the unavailability will be $q+\Delta q$ after the test. The impacts of a deleterious test can be handled by the perturbation approaches described earlier.

Finally, the surveillance test importances can be implemented in a variety of ways. A criterion, such as the safety goal, can be used to screen the important surveillance tests. The importances can also be ranked in a relative manner to identify and categorize the most risk important tests. "Class 1 tests", "Class 2 tests", etc., can therefore be identified. The importances can thus be used to focus testing-related activities and programs.

4.9 Evaluation of Test and Maintenance Importances for Arkansas Nuclear (ANO)

Using the models described in the previous sections, the importances of corrective maintenances and surveillance tests were calculated for Arkansas Nuclear (ANO-1) based on the Arkansas Nuclear PRA. Corrective maintenance importances and surveillance test importances were calculated at the system, subsystem, and component level. All the systems, subsystems, and components analyzed in the ANO study were evaluated for their importances. The risk characteristic used for all the evaluations was the core melt frequency. Summaries of the results are given here to show the type of values and patterns which are obtained. As will be seen the importances clearly differentiate important test and maintenances from unimportant tests and maintenances. This is one of the most useful properties of not only these particular importances, but all of the importances discussed in this report. Evaluation of importances allows the focusing and prioritization of resources to be effectively made.

4.9.1 Importances of Corrective Maintenances

All the corrective maintenance importances were calculated based on the Birnbaum importance measure R(1)-R(0). Any reconfigurations which might be done to mitigate the effects of a downed system, subsystem, or component were not taken into account. These actions would tend to decrease the risk impact of the downed state and consequently decrease the corrective maintenance importance. Hence the importances are bounding values for those cases when reconfiguration is performed.

Table 1 gives the corrective maintenance, or Birnbaum, importances for the ANO-1 safety systems, arranged in decreasing order. The Birnbaum importance gives the increase in core melt frequency when the system is down as compared to when it is up. With regard to the importance of corrective action, the Birnbaum importance thus equivalently gives the reduction in core melt frequency in effectively restoring the system from a failed state to an operable state.

As seen from Table 1, there is a five order of magnitude variation (a factor of 100,000) in the importance of a system being down and hence of corrective restoration of the system being down. This wide variation of values allows effective discriminations to be made of maintenance importances. This allows implementations to be sharply focused. Also the impacts of PRA uncertainties are smaller than this wide variation in importance. Figure 12 is a bar graph of the system maintenance importances. The vertical labels on the graph use "maintenance impact" instead of "maintenance importance". The scale on the right is the maintenance importance, or equivalently the maintenance impact, divided by the safety goal value of 1×10^{-4} per reactor year for core melt frequency; this scale indicates how much higher the core melt frequency is than the safety goal when the system is down. The tic marks on the vertical scales represent order of magnitude (factor of 10) variations, again showing the large variation in importances.

Table 2 shows the corrective maintenance importances, or equivalently the downed importances, for the ANO subsystems. Figure 13 is a bar graph of these importances. There is almost a four order of magnitude variation (a factor of 10,000) in importance at the subsystem level. The

TABLE 1. CORRECTIVE MAINTENANCE IMPORTANCES FOR ANO-1 SAFETY SYSTEMS

System	System Identifier	Maintenance Importance
Emergency DC Power	DC Power	8.5
Reactor Protection System	RPS	8.5×10^{-1}
Emergency AC Power	AC Power	1.1×10^{-1}
Service Water System	SWS	3.1×10^{-1}
Emergency Feedwater System	EFWS	2.7×10^{-2}
Emergency Feedwater Initiation and Control System	EFICS	2.7×10^{-2}
Battery and Switchgear Emergency Cooling System	ECS	2.4×10^{-2}
Safety Relief System	SRS	2.3×10^{-2}
High Pressure Injection System	HPIS	2.0×10^{-3}
Engineered Safeguards Actuation System	ESAS	1.3×10^{-3}
Low Pressure Recirculation System	LPRS	1.2×10^{-3}
High Pressure Recirculation System	HPRS	1.0×10^{-3}
Low Pressure Injection System	LPIS	2.4×10^{-4}
Power Conversion System	PCS	1.7×10^{-4}
Core Flood System	CFS	8.7×10^{-5}

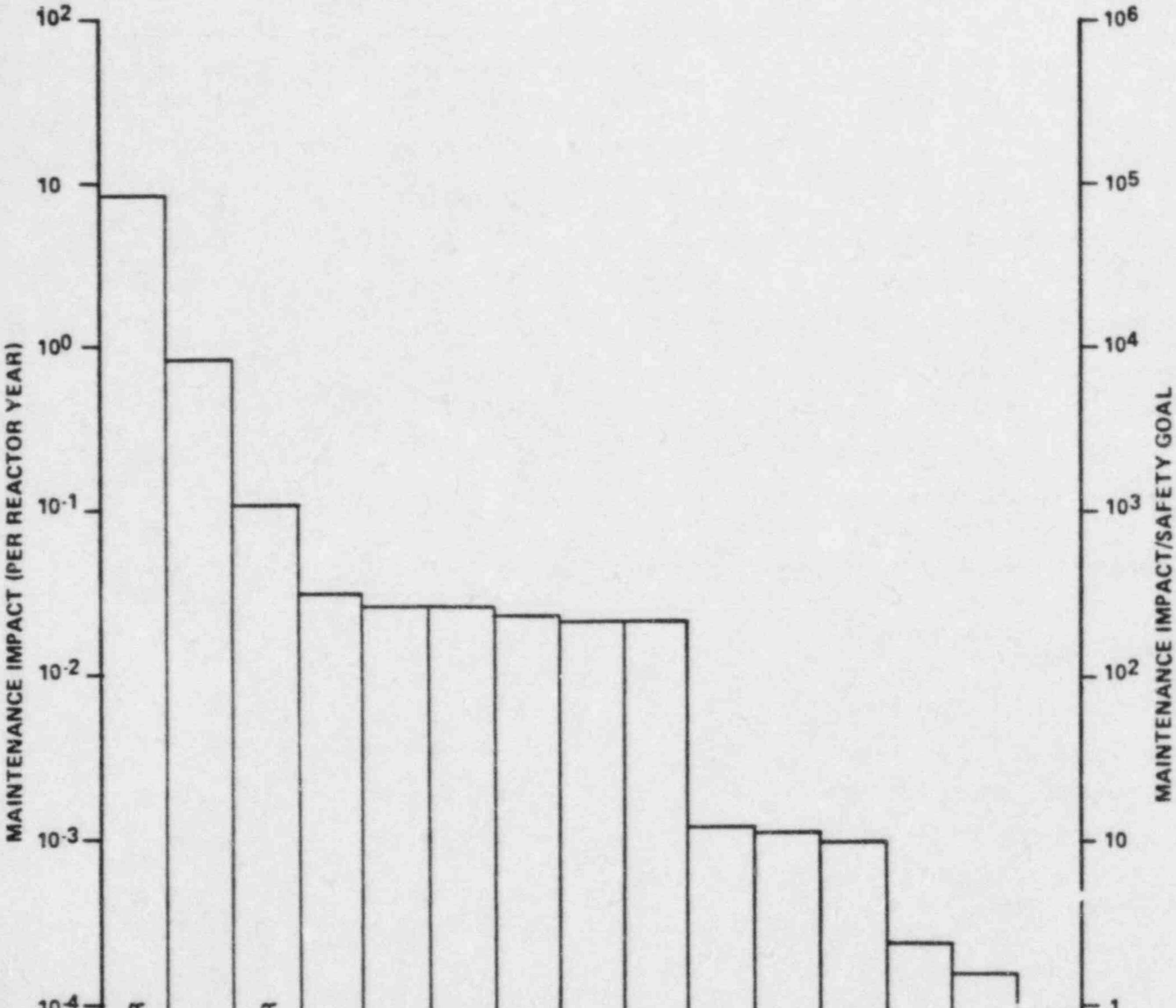

FIGURE 12. MAINTENANCE IMPACTS (IMPORTANCES) FOR ANO-1 SAFETY SYSTEMS

TABLE 2. CORRECTIVE MAINTENANCE IMPORTANCES FOR ANO-1 SAFETY SUBSYSTEMS

Subsystem	Subsystem Identifier	Maintenance Importance
Emergency Onsite DC Power	DC Onsite	3.3×10^{-1}
Emergency Odd DC Power	DC Odd	6.2×10^{-2}
Emergency Even DC Power	DC Even	3.1×10^{-2}
Safety Relief Valves Failure to Open	SRS Open	2.3×10^{-2}
Emergency Odd AC Power	AC Odd	1.2×10^{-2}
Emergency Feedwater Initiation and	EFICS C	
Control System Vector C	EFICS C	1.2×10^{-2}
Emergency Feedwater System Train A (Turbine Driven)	EFWS B	6.4×10^{-3}
Emergency Even AC Power	AC Even	5.6×10^{-3}
Service Water System Loop 1	SWS 1	5.0×10^{-3}
Safety Relief Valves to Close	SRS Close	4.5×10^{-3}
Battery and Switchgear Emergency Cooling System Chill Water Train A	ECS CW A	3.9×10^{-3}
Emergency Onsite AC Power	AC Onsite	3.5×10^{-3}
Standby HPIS Pump	HPIS C	3.0×10^{-3}
Service Water System Loop	SWS 2	2.6×10^{-3}
Battery and Switchgear Emergency Cooling System Chill Water Train B	ECS CW B	2.3×10^{-3}
Engineered Safeguards Actuation System Digital 1	ESAS D1	2.2×10^{-3}
Reactor Protection System Channel A	RPS A	1.7×10^{-3}
Reactor Protection System Channel B	RPS B	1.7×10^{-3}
Emergency Feedwater Initiation and Control System Initiation B	EFICS B	1.5×10^{-3}
Normally Operating and Aligned Standby HPIS Pumps	HPIS AB	1.2×10^{-3}

TABLE 2. CONTINUED

Subsystem	Subsystem Identifier	Maintenance Importance
Engineered Safeguards Actuation System Digital 2	ESAS D2	1.1×10^{-3}
Reactor Protection System Channel C	RPS C	8.5×10^{-4}
Reactor Protection System Channel D	RPS D	8.5×10^{-4}
Emergency Feedwater Initiation and Control System Initiation A	EFICS A	6.5×10^{-4}
Engineered Safeguards Actuation System Analog 1	ESAS A1	5.0×10^{-4}
Engineered Safeguards Actuation System Analog 2	ESAS A2	5.0×10^{-4}
Engineered Safeguards Actuation System Analog 3	ESAS A3	5.0×10^{-4}
Emergency Feedwater Initiation and Control System Vector D	EFICS D	2.8×10^{-4}
Emergency Feedwater System Train A (Motor Driven)	EFWS A	2.8×10^{-4}
Low Pressure Recirculation Train B	LPRS B	1.0×10^{-4}
Low Pressure Recirculation Train A	LPRS A	9.6×10^{-5}
Core Flood System Train A	CFS A	8.7×10^{-5}
Core Flood System Train B	CFS B	8.7×10^{-5}
High Pressure Recirculation Trains A and B	HPRS AB	6.9×10^{-5}
High Pressure Recirculation Train C	HPRS C	6.8×10^{-5}
Low Pressure Injection Train B	LPIS B	3.0×10^{-5}
Low Pressure Injection Train A	LPIS A	2.6×10^{-5}
Battery and Switchgear Emergency Cooling System Refrigerated Unit A	ECS REF A	1.9×10^{-5}
Battery and Switchgear Emergency Cooling System Refrigerated Unit B	ECS REF B	1.6×10^{-5}

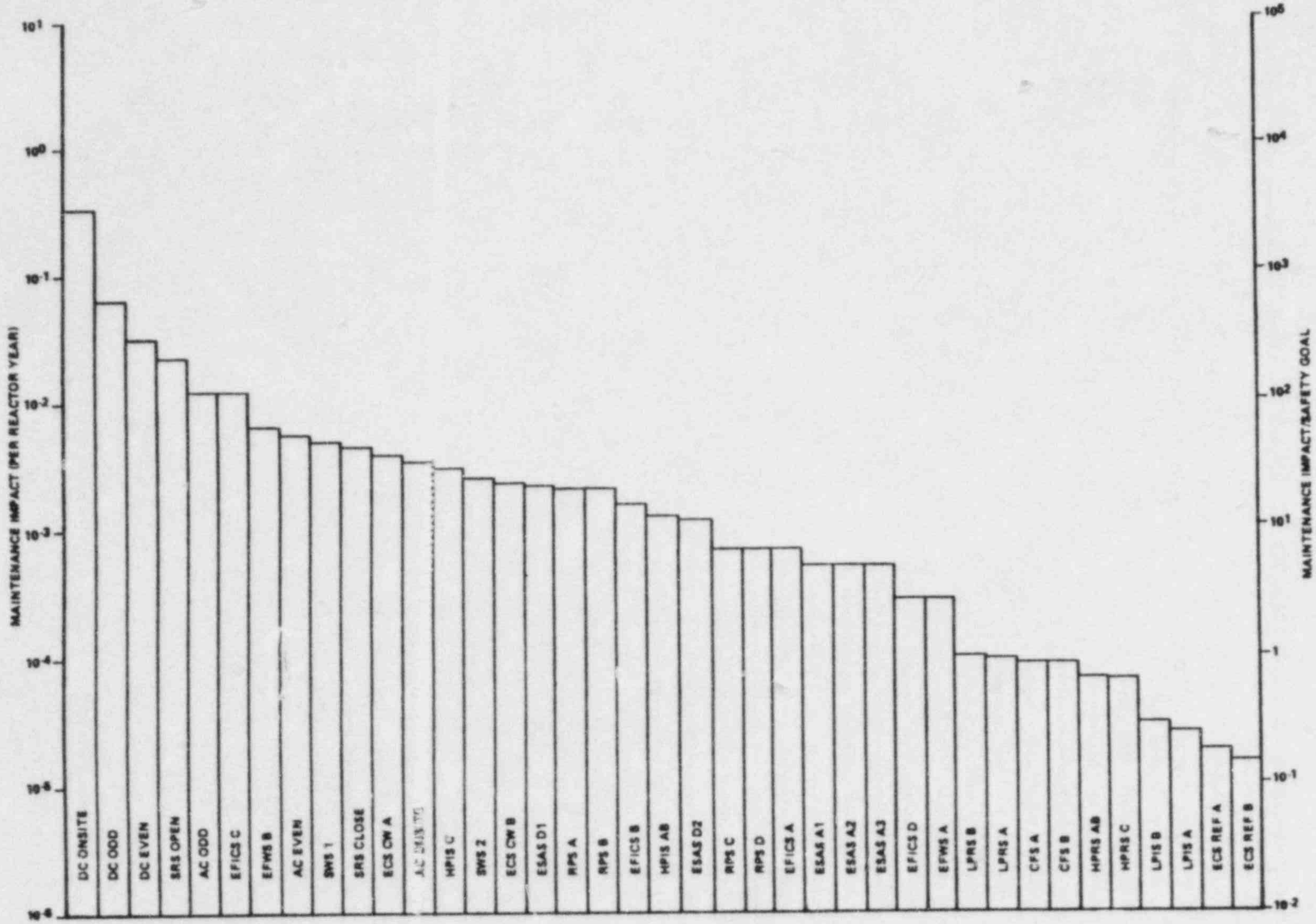

FIGURE 13. MAINTENANCE IMPACTS (IMPORTANCES) AT THE SUBSYSTEM LEVEL

subsystems of more importance are those associated with emergency power, the safety relief valves, and emergency feedwater. The subsystems of least importance are a single train of high pressure recirculation and low pressure injection, and a single refrigerated unit of the cooling system.

Table 3 shows the components having the highest maintenance importances at ANO, again arranged in decreasing order. A total of 522 components were evaluated for their importances. The importances varied by more than seven orders of magnitude (a factor of 10,000,000) at the component level. Table 4 gives a categorization of all the component maintenance importances, in order of magnitude (factor of 10) categories. As observed, 12 components, or 2 percent of the components, have importances between 1×10^{-2} and 1×10^{-1} while 95 components, or 18 percent, have importances less than 1×10^{-6}. There are relatively few corrective maintenances which are highly important and which need to be focused upon, while a significant number are not critical.

4.9.2 Importances of Surveillance Tests

The importance of a surveillance test was calculated by multiplying the Birnbaum importance by the appropriate unavailability. This particular importance measure is the Fussell-Vesely importance. The Fussell-Vesely importance gives the expected contribution to the core melt frequency (the risk characteristic used) from the system, subsystem, or component being down. Equivalently, the Fussell-Vesely importance gives the expected reduction in core melt frequency from checking whether the system, subsystem, or component is up.

Table 5 gives the surveillance test importances for the ANO safety systems. Figure 14 gives the bar graph of the importances. The vertical scales on the figure are labeled "test impact" which is equivalent to "test importance". The right hand vertical scale divides the impact (importance) by the safety goal value of 1×10^{-4} per reactor year for the core melt frequency; this ratio gives the contribution compared to the safety goal value. There is almost a four order of magnitude variation (a factor of 10,000) in the importances with the emergency cooling system and emergency

TABLE 3. COMPONENTS WITH HIGHEST MAINTENANCE IMPORTANCES AT ANO-1

Local Fault	Component	Maintenance Importance
LF-DC-D01	BUS D01	6.2E-02
LF-DC-D02	BUS D02	3.1E-02
LF-EFW-E22	VALVE CHECK CC CS99	2.7E-02
LF-SWS-S50	VALVE M.O. OC CV3824	2.7E-02
LF-EFW-E22	VALVE MANUAL OC CS19	2.7E-02
LF-EFW-E22	VALVE CHECK CC CS98	2.7E-02
LF-EFW-E22	TANK T41	2.7E-02
LF-LPI-L25	VALVE MANUAL OC BW1X	2.4E-02
LF-AC-A3	BUS A3	1.2E-02
LF-AC-A3	CIRCUIT BREAKER 114	1.2E-02
LF-EFC-D1D2	SHARED SIGNAL PATH D1-D2	1.1E-02
LF-EFW-E2	VALVE CHECK CC FW13B	1.0E-02
LF-DC-RS2INV	BUS 120VAC RS2	7.7E-03
LF-DC-RS1INV	BUS 120VAC RS1	7.0E-03
LF-EFW-E11	PUMP TURBINE DRIVEN P7A	6.4E-03
LF-EFW-E8	VALVE CHECK CC FW10B	6.4E-03
LF-EFW-E21	VALVE M.O. OC CV2802	6.4E-03
LF-EFW-E17	VALVE MANUAL CO FW11A	6.4E-03
LF-EFW-E16	VALVE MANUAL CO FW12A	6.4E-03
LF-EFW-E43	VALVE RELIEF CO PSV6602	6.4E-03
LF-AC-B5	CIRCUIT BREAKER 512	5.8E-03
LF-AC-B5	TRANSFORMER X5	5.8E-03
LF-AC-B5	BUS B5	5.8E-03
LF-AC-B5	CIRCUIT BREAKER 301	5.8E-03
LF-AC-B6	TRANSFORMER X6	5.6E-03
LF-AC-B6	CIRCUIT BREAKER 612	5.6E-03
LF-AC-B6	BUS B6	5.6E-03
LF-AC-A4	CIRCUIT BREAKER 214	5.6E-03
LF-AC-A4	BUS A4	5.6E-03
LF-AC-B6	CIRCUIT BREAKER 401	5.6E-03
LF-SWS-S1	VALVE CHECK OC 001C	4.9E-03
LF-SWS-S1	VALVE MANUAL OC 002C	4.9E-03
LF-SWS-S1	PUMP MOTOR DRIVEN P4C	4.9E-03
LF-AC-B62	BUS B62	3.9E-03
LF-AC-B62	CIRCUIT BREAKER 614	3.9E-03
LF-DC-D21	BUS D21	3.9E-03
LF-DC-D21	CIRCUIT BREAKER D02	3.9E-03
LF-ECS-A6	VALVE MANUAL OC AC45D	3.8E-03
LF-SWS-VCH4A	VALVE MANUAL OC SW600A	3.8E-03
LF-ECS-A4	VALVE MANUAL OC AC206A	3.8E-03
LF-SWS-VCH4A	VALVE MANUAL OC SW602A	3.8E-03
LF-SWS-VCH4A	VALVE M.O. 3 WAY CV6034	3.8E-03
LF-SWS-VCH4A	VALVE MANUAL OC SW3903	3.8E-03
LF-ECS-A8	VALVE MANUAL OC AC44D	3.8E-03
LF-SWS-VCH4A	THERMOSTAT UNIT VCH4A	3.8E-03
LF-SWS-VCH4A	VALVE MANUAL OC SW3905	3.8E-03
LF-SWS-VCH4A	CHILL WATER UNIT VCH4A	3.8E-03
LF-SWS-VCH4A	VALVE CHECK CC SW604A	3.8E-03
LF-SWS-VCH4A	VALVE MANUAL OC AC200A	3.8E-03
LF-ECS-A6	FAN VUC2D	3.8E-03
LF-SWS-VCH4A	VALVE MANUAL OC SW608A	3.8E-03
LF-ECS-A2	VALVE MANUAL OC AC41D	3.8E-03
LF-SWS-VCH4A	VALVE MANUAL OC SW606A	3.8E-03
LF-EFW-E1	VALVE CHECK CC FW13A	3.7E-03
LF-AC-B51	CIRCUIT BREAKER 521	3.7E-03
LF-AC-B51	BUS B51	3.7E-03
LF-AC-B61	CIRCUIT BREAKER 621	3.4E-03
LF-AC-B61	BUS B61	3.4E-03
LPI1408B-VCC-LF	VALVE M.O. CC CV1408B	3.0E-03
LF-HPI-H14	VALVE M.O. CC CV3810	2.9E-03
LF-HPI-H14	VALVE CHECK CC MU19C	2.9E-03
LF-HPI-H14	PUMP MOTOR DRIVEN P36C	2.9E-03
LF-HPI-H14	VALVE MANUAL OC MU18C	2.9E-03
LF-HPI-H14	VALVE MANUAL OC MU20C	2.9E-03

TABLE 4. CATEGORIZATION OF COMPONENT MAINTENANCE IMPORTANCES FOR ANO-1

Range of Importance Value	Number (Percent) of Components in this Range	
$1 \times 10^{-2} - 1 \times 10^{-1}$	12	(2%)
$1 \times 10^{-3} - 1 \times 10^{-2}$	108	(21%)
$1 \times 10^{-4} - 1 \times 10^{-3}$	78	(15%)
$1 \times 10^{-5} - 1 \times 10^{-4}$	125	(24%)
$1 \times 10^{-6} - 1 \times 10^{-5}$	104	(20%)
$< 1 \times 10^{-6}$	95	(18%)
TOTAL	522	(100%)

TABLE 5. TEST IMPORTANCES FOR ANO-1 SAFETY SYSTEMS

	System Identifier	Test Importances
Battery and Switchgear Emergency Cooling System	ECS	1.5×10^{-4}
Emergency DC Power	DC Power	1.3×10^{-4}
Emergency AC Power	AC Power	1.1×10^{-4}
Safety Relief System	SRS	1.0×10^{-4}
High Pressure Injection System	HPIS	7.0×10^{-5}
Service Water System	SWS	6.3×10^{-5}
Emergency Initiation and Control System	EFICS	4.2×10^{-5}
Emergency Feedwater System	EFWS	4.1×10^{-5}
Engineered Safeguards Actuation System	ESAS	1.8×10^{-5}
Power Conversion System	PCS	1.1×10^{-5}
Low Pressure Recirculation System	LPRS	3.9×10^{-6}
Reactor Protection System	RPS	3.6×10^{-6}
Low Pressure Injection System	LPIS	2.0×10^{-6}
High Pressure Recirculation System	HPRS	1.0×10^{-6}
Core Flood System	CFS	4.5×10^{-8}

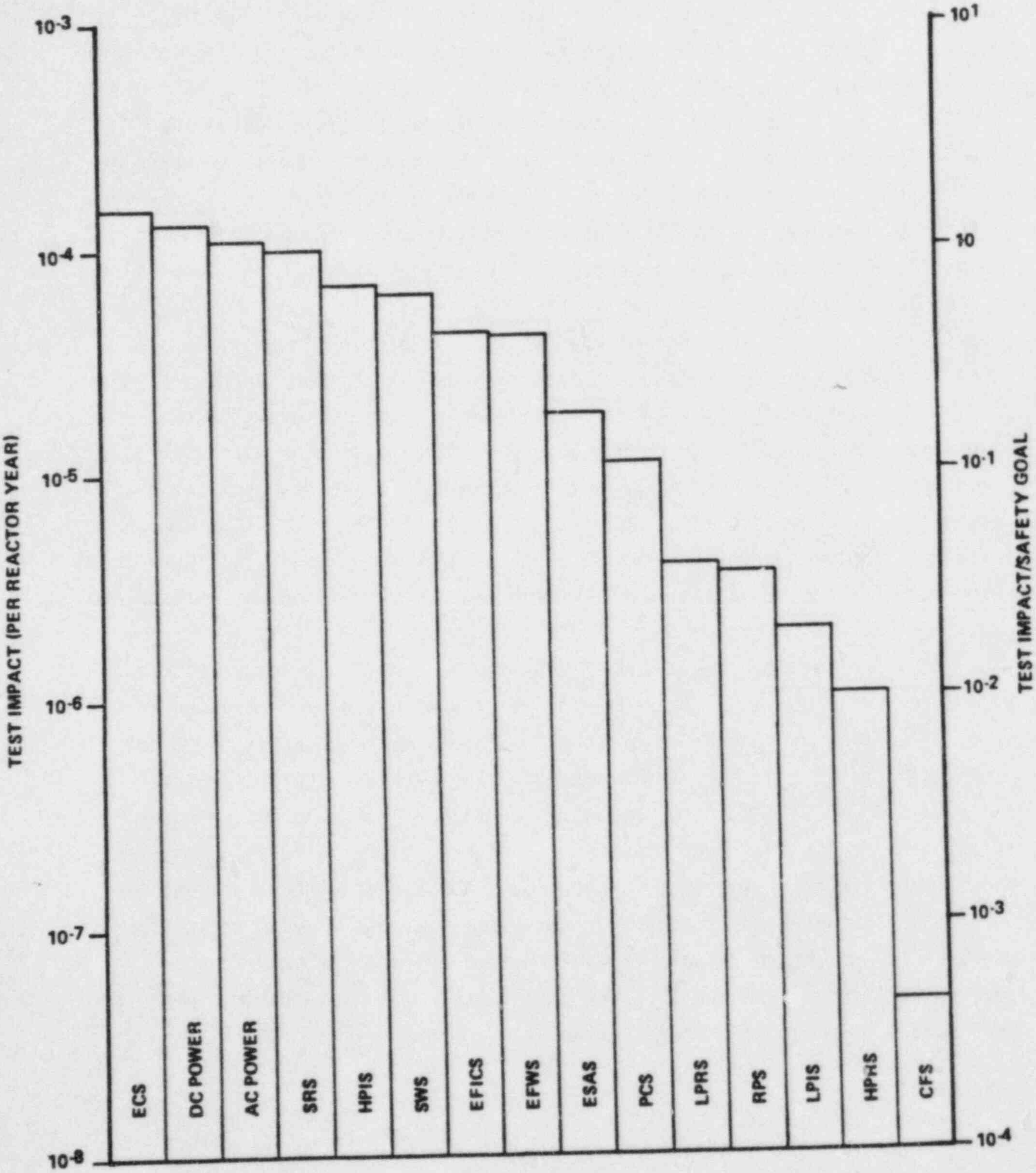

FIGURE 14. TEST IMPACTS (IMPORTANCES) FOR ANO-1 SAFETY SYSTEMS

power systems having the highest test importance and the core flood system having the lowest importance. There is thus again an effective discrimination of the important tests from the unimportant ones.

Table 6 shows the test importances at the subsystem level and Figure 15 shows the bar graph of these importances. The importances vary by almost three orders of magnitude, or a factor of 1,000. The subsystems of highest test importance are those associated with emergency power, a single train of the cooling system and safety relief valves (failure to close as opposed to failure to open in the maintenance case). The subsystem having least test importance are single train tests on the core flood system.

The individual component tests having highest importances are shown in Table 7. Table 8 gives a categorization of all the component test importances in order of magnitude (factor of 10) categories. As observed, 26 component tests, or 5 percent, reduce the core melt frequency per test by values in the range of 1×10^{-5} to 1×10^{-4}. As also observed, 188 component tests, or 36 percent, reduce the frequency by less than 1×10^{-9}. There are relatively few important tests while there are a larger number of unimportant tests.

Finally, Figures 16 and 17 show the correlation of component test importances with component maintenance importances which were computed in the previous section. Figure 16 plots the components of highest test importance (the upper graph) and shows their corresponding maintenance importance. Table 9 shows the key for the component identification numbers (component ID's). Figure 17 plots the components of highest maintenance importance and shows their corresponding test importances. As observed, there is some correlation between importances, however since the test importance has the extra factor of the unavailability which can significantly vary, the importances do not necessarily track each other. This is not surprising since the importances measure different things.

TABLE 6. TEST IMPORTANCES FOR ANO-1 SAFETY SUBSYSTEMS

Subsystem	Subsystem Identifier	Test Importance
Emergency Odd DC power	DC Odd	1.2×10^{-4}
Battery and Switchgear Emergency Cooling System Chill Water Train A	ECS CW A	1.1×10^{-4}
Safety Relief Values Failure to Close	SRS Close	1.0×10^{-4}
Emergency Odd AC Power	AC Odd	6.6×10^{-5}
Standby HPIS Pump	HPIS C	6.5×10^{-5}
Battery and Switchgear Emergency Cooling System Chill Water Train B	ESC CW B	6.4×10^{-5}
Emergency Feedwater Initiation and Control System Vector C	EFICS C	5.4×10^{-5}
Service Water System Loop 1	SWS 1	4.8×10^{-5}
Emergency Even DC Power	DC Even	4.1×10^{-5}
Emergency Feedwater Initiation and Control System Initiation A	EFICS A	3.4×10^{-5}
Emergency Feedwater System Train A (Turbine Driven)	EFWS B	3.0×10^{-5}
Emergency Onsite DC Power	DC Onsite	2.8×10^{-5}
Emergency Onsite AC Power	AC Onsite	2.5×10^{-5}
Service Water System Loop 2	SWS 2	1.8×10^{-5}
Emergency Feedwater Initiation and Control System Initiation B	EFICS B	1.2×10^{-5}
Emergency Even AC Power	AC Even	1.2×10^{-5}
Normally Operating and Aligned Standby HPIS Pumps	HPIS AB	1.0×10^{-5}
Engineered Safeguards Actuation System Analog 1	ESAS A1	6.0×10^{-6}
Engineered Safeguards Actuation System Analog 2	ESAS A2	6.0×10^{-6}
Engineered Safeguards Actuation System Analog 3	ESAS A3	6.0×10^{-6}

TABLE 6. CONTINUED

Subsystem	Subsystem Identifier	Test Importance
Emergency Feedwater Train A (Motor Driven)	EFWS A	4.1×10^{-6}
Low Pressure Recirculation Train A	LPRS A	2.5×10^{-6}
Low Pressure Recirculation Train B	LPRS B	2.5×10^{-6}
Reactor Protection System Channel A	RPS A	1.7×10^{-6}
Reactor Protection System Channel B	RPS B	1.7×10^{-6}
Reactor Protection System Channel C	RPS C	1.7×10^{-6}
Reactor Protection System Channel D	RPS D	1.7×10^{-6}
Emergency Feedwater Initiation and Control System Vector D	EFICS D	1.4×10^{-6}
Low Pressure Injection Train B	LPIS B	1.3×10^{-6}
Low Pressure Injection Train A	LPIS A	1.2×10^{-6}
High Pressure Recirculation Trains A and B	HPRS AB	1.0×10^{-6}
High Pressure Recirculation Train C	HPRS C	1.0×10^{-6}
Safety Relief Valves Failure to Open	SRS Open	3.2×10^{-7}
Engineered Safeguards Actuation System Digital 1	ESAS D1	1.2×10^{-7}
Engineered Safeguards Actuation System Digital 2	ESAS D2	1.2×10^{-7}
Battery and Switchgear Emergency Cooling System Refrigerated Unit A	ECS REF A	1.1×10^{-7}
Battery and Switchgear Emergency Cooling System Refrigerated Unit B	ECS REF B	9.0×10^{-8}
Core Flood System Train A	CFS A	4.5×10^{-8}
Core Flood System Train B	CFS B	4.5×10^{-8}

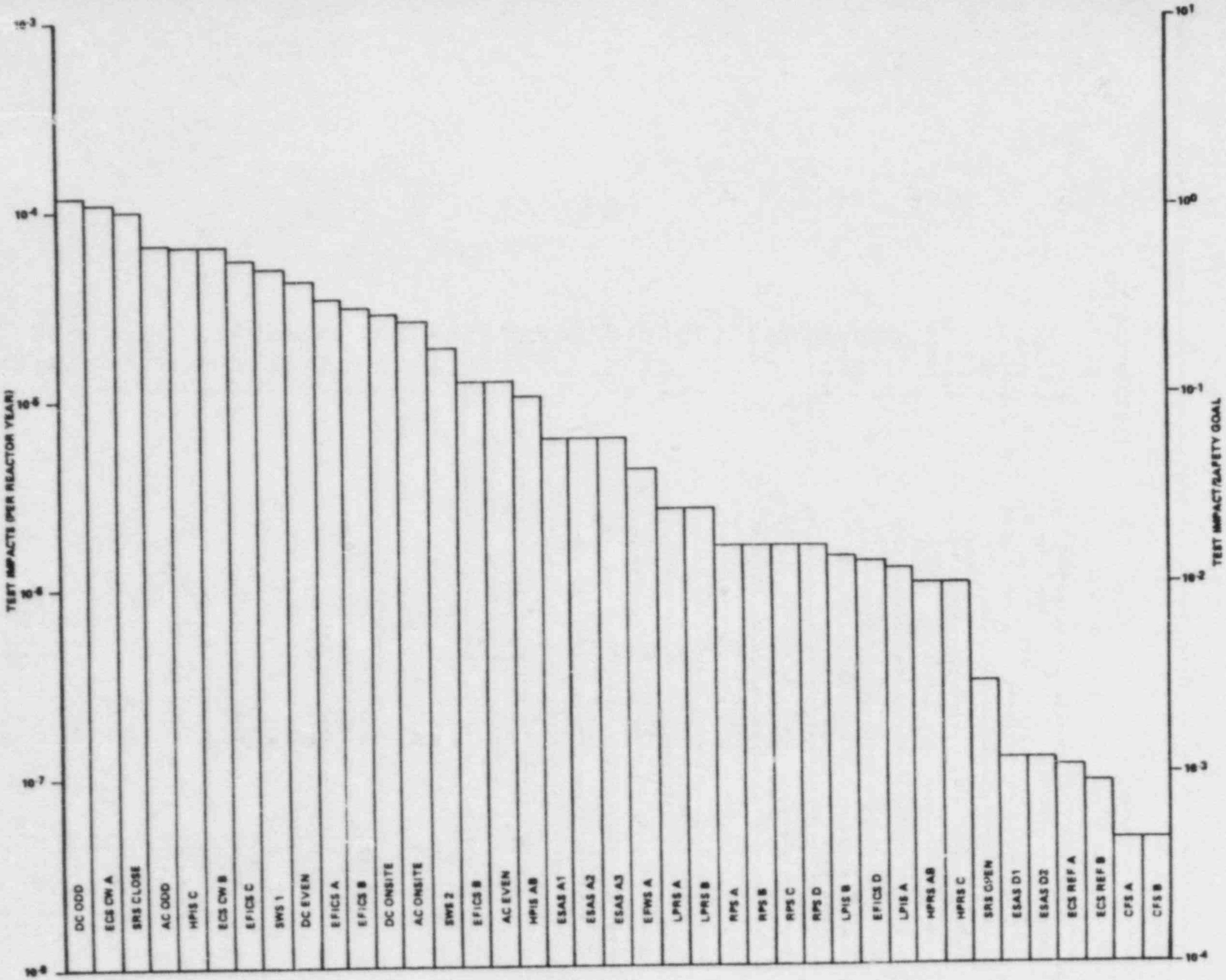

FIGURE 15. TEST IMPACTS (IMPORTANCES) AT THE SUBSYSTEM LEVEL

TABLE 7
COMPONENTS WITH HIGHEST TEST IMPORTANCES AT ANO-1

LOCAL FAULT	COMPONENT	TEST IMPORTANCE
LF-EFC-D1D2	SHARED SIGNAL PATH D1-D2	5.1E-05
SRV1	VALVE SAFETY RELIEF 1	5.0E-05
SRV2	VALVE SAFETY RELIEF 2	5.0E-05
LF-SWS-VCH4A	VALVE M.O. 3 WAY CV6034	3.1E-05
LF-SWS-VCH4A	CHILL WATER UNIT VCH4A	3.0E-05
LPI1408B-VCC-LF	VALVE M.O. CC CV1408B	2.5E-05
LF-SWS-S1	PUMP MOTOR DRIVEN P4C	2.4E-05
LF-HPI-H14	VALVE M.O. CC CV3810	2.4E-05
LF-SWS-S14	VALVE M.O. OO CV3820	2.2E-05
LF-EFC-ACBD4	SIGNAL PATHS AC04-BD04	2.2E-05
LF-SWS-S5	VALVE M.O. OO CV3643	2.2E-05
LF-SWS-VCH4A	THERMOSTAT UNIT VCH4A	2.1E-05
LF-EFW-E11	PUMP TURBINE DRIVEN P7A	2.0E-05
LF-ECS-A6	FAN VUC2D	1.8E-05
LF-SWS-VCH4B	VALVE M.O. 3 WAY CV6036	1.8E-05
LF-SWS-VCH4B	CHILL WATER UNIT VCH4B	1.7E-05
LF-AC-DG1	DIESEL GENERATOR DG1	1.7E-05
LF-HPI-H14	PUMP MOTOR DRIVEN P36C	1.6E-05
LF-EFW-E6	VALVE M.O. CC CV2626	1.6E-05
LF-EFC-VCD2	SIGNAL PATH VCD2	1.4E-05
LF-SWS-S2	PUMP MOTOR DRIVEN P4B	1.3E-05
LF-SWS-VCH4B	THERMOSTAT VCH4B	1.2E-05
LF-EFW-E4	VALVE M.O. CC CV2620	1.2E-05
LF-EFW-E29	VALVE M.O. CC CVY2	1.2E-05
LPI1407A-VCC-LF	VALVE M.O. CC CV1407A	1.1E-05
LF-ECS-B6	FAN VUC2B	1.0E-05
LF-EFC-ABCD4	SIGNAL PATHS AB04-CD04	8.3E-06
LF-EFC-B87B1	SIGNAL PATHS AC6-BD6	8.1E-06
LF-EFW-E6	VALVE M.O. OC CVX-2	7.8E-06
LF-AC-DG2	DIESEL GENERATOR DG2	6.7E-06
LF-EFW-E4	VALVE M.O. OC CVX-1	6.2E-06
LF-ESF-TA01	SIGNAL PATH TA01 ANALOG	6.1E-06
LF-ESF-TC01	SIGNAL PATH TC01 ANALOG	6.1E-06
LF-ESF-TB01	SIGNAL PATH TB01 ANALOG	6.1E-06
LF-EFC-CSY2	SIGNAL PATH CSY2	5.9E-06
LF-DC-D01	BUS D01	4.5E-06
LF-SWS-S62	VALVE M.O. CC CV3806	3.7E-06
LF-EFC-AA7B2	SIGNAL PATHS AB6-CD6	3.4E-06
LF-EFW-E22	VALVE MANUAL OC CS19	2.7E-06
LF-EFW-E22	VALVE CHECK CC CS99	2.7E-06
LF-EFW-E22	VALVE CHECK CC CS98	2.7E-06
LF-LPI-L25	VALVE MANUAL OC BW1X	2.4E-06
LF-EFC-VCD1	SIGNAL PATH VCD1	2.3E-06
LF-EFC-VE04	SIGNAL PATH VE04	2.2E-06
LF-DC-D02	BUS D02	2.2E-06
LF-DC-D06	BATTERY D06	2.2E-06
LF-EFC-VE02	SIGNAL PATH VE02	2.1E-06
LF-DC-D07	BATTERY D07	2.1E-06
LF-AC-A3	CIRCUIT BREAKER 114	2.0E-06
LF-EFW-E28	VALVE M.O. CC VCY1	2.0E-06
LF-SWS-S63	VALVE M.O. CC CV3807	2.0E-06
LF-ECS-B5	FAN VUC14D	1.8E-06
RPS000AA	BREAKER CC A	1.7E-06
LF-EFW-E3	VALVE M.O. CC CV2670	1.7E-06
LF-EFW-E5	VALVE M.O. OC CV2627	1.7E-06
RPS000BB	BREAKER CC B	1.7E-06
LF-EFW-E10	PUMP MOTOR DRIVEN P7B	1.5E-06
LF-DC-RS2INV	BUS 120VAC RS2	1.4E-06
LF-DC-RS1INV	BUS 120VAC RS1	1.3E-06
LF-EFC-5161	SHARED SIGNAL PATH S1-61	1.3E-06
LF-EFC-VC51	SIGNAL PATH VC51	1.2E-06
LF-SWS-S83	VALVE M.O. CC CV3821	1.1E-06
LF-EFW-E2	VALVE CHECK CC FW13B	1.0E-06
LF-SWS-S82	VALVE M.O. CC CV3822	1.0E-06
LF-AC-DG1	CIRCUIT BREAKER 308	1.0E-06

TABLE 8. CATEGORIZATION OF COMPONENT TEST IMPORTANCES FOR ANO-1

Range of Importance Value	Number (Percent) of Components in This Range	
$1 \times 10^{-5} - 1 \times 10^{-4}$	26	(5%)
$1 \times 10^{-6} - 1 \times 10^{-5}$	39	(7%)
$1 \times 10^{-7} - 1 \times 10^{-6}$	96	(18%)
$1 \times 10^{-8} - 1 \times 10^{-7}$	50	(10%)
$1 \times 10^{-9} - 1 \times 10^{-8}$	123	(24%)
$< 1 \times 10^{-9}$	188	(36%)
	522	(100%)

FIGURE 16. MAINTENANCE IMPORTANCE VERSUS TEST IMPORTANCE FOR ANO-1

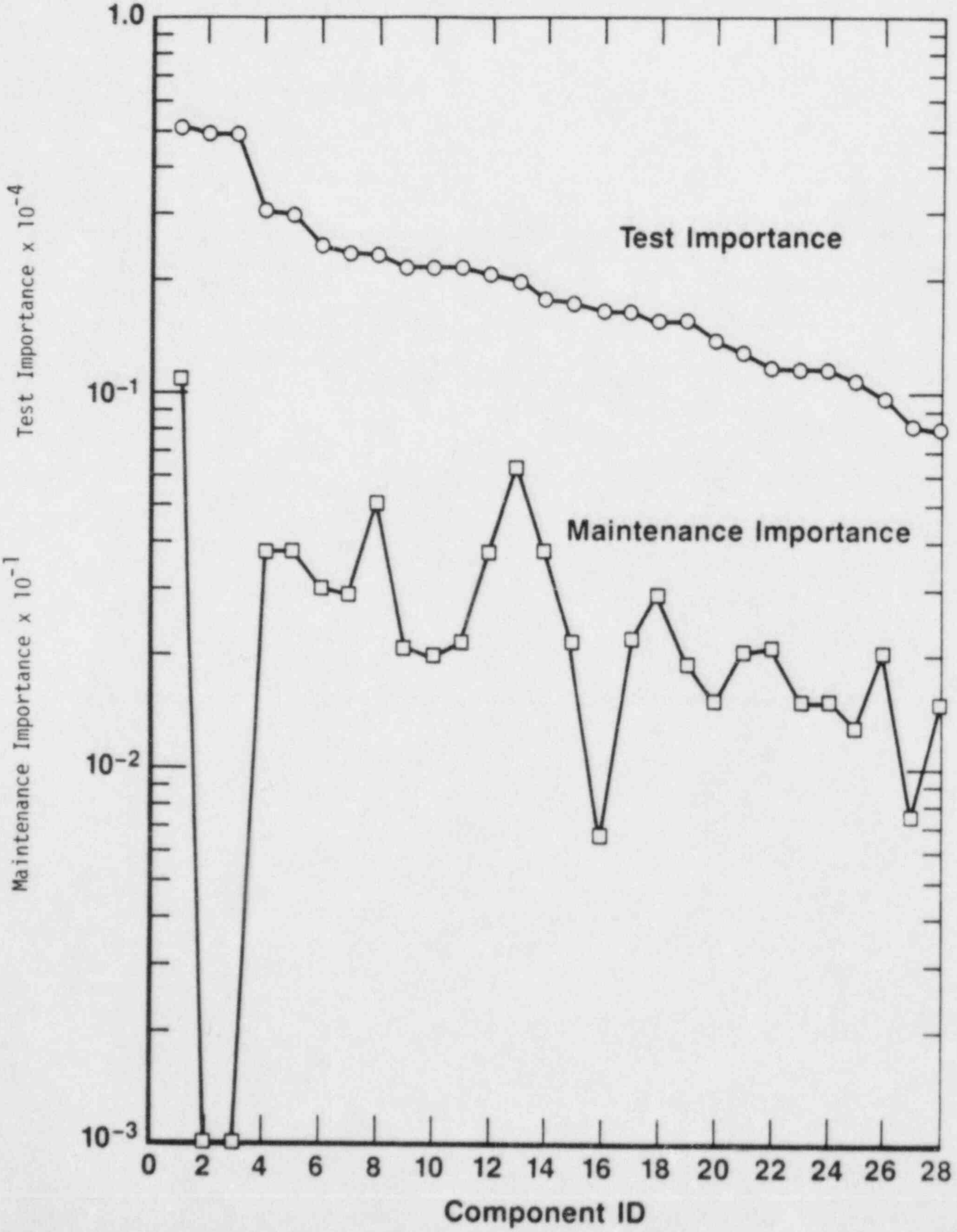

FIGURE 17. TEST IMPORTANCE VERSUS MAINTENANCE IMPORTANCE FOR ANO-1

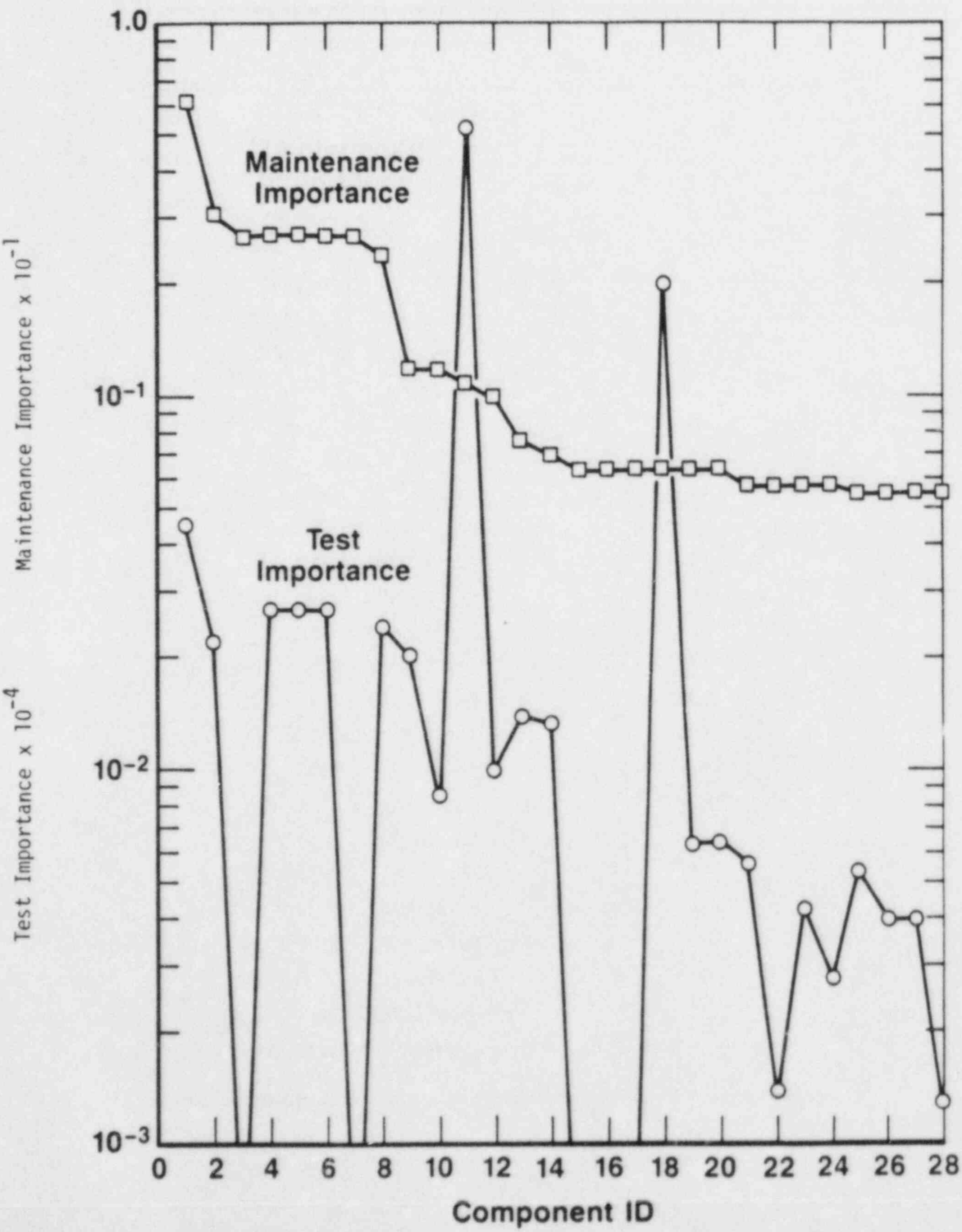

TABLE 9. COMPONENT ID FOR FIGURE 16

ID	Component
1	Shared Signal Pa:h D1-D2
2	Valve Safety Relief 1
3	Valve Safety Relief 2
4	Valve M.O. 3 Way CV6034
5	Chill Water Unit VCH4A
6	Valve M.O. CC CV1408B
7	Valve M.O. CC CV3810
8	Pump Motor Drive P4C
9	Valve M.O. 00CV3643
10	Signal Paths AC04-BD04
11	Valve M.O. 00CV3820
12	Thermostat Unit VCH4A
13	Pump Turbine Drive P7A
14	Fan VUC2D
15	Valve M.O. 3 Way CV6036
16	Diesel Generator DG1
17	Chill Water Unit VCH4B
18	Pump Motor Driven P36C
19	Valve M.O. CC CV2626
20	Signal Path VCD2
21	Pump Motor Drive P4B
22	Thermostat VCH4B
23	Valve M.O. CC CV2620
24	Valve M.O. CC CVY2
25	Valve M.O. CC CV1407A
26	Fan VUC2B
27	Signal Paths AB04-CD04
28	Signal Paths AC6-BD6

TABLE 10. COMPONENT ID FOR FIGURE 17

ID	Component
1	Bus D01
2	Bus D02
3	Tank T41
4	Valve Manual OC CS19
5	Valve Check CC CS08
6	Valve Check CC CS99
7	Valve M.O. OC CV3824
8	Valve Manual OC BW1X
9	Circuit Breaker 114
10	Bus A3
11	Shared Signal Path D1-D2
12	Valve Check CC FW13B
13	Bus 120VAC RS2
14	Bus 120VAC RS1
15	Valve Manual CO FW12A
16	Valve Manual CO FW11A
17	Valve Relief CO PSV6602
18	Pump Turbine Drive P7A
19	Valve Check CCFW10B
20	Valve M.O. OC CV2802
21	Circuit Breaker 301
22	Circuit Breaker 512
23	Bus B5
24	Transformer X5
25	Circuit Breaker 401
26	Bus B6
27	Bus A4
28	Circuit Breaker 612

5. Root Cause Importance Evaluations

This section describes a special type of importance evaluation termed root cause importance evaluations. For root cause importance evaluations, the component failure rate is decomposed into specific causes of failure and the importance of a specific cause is then determined. Specific causes of failure for example can include design errors, manufacturing errors, quality control errors, or installation errors. Root cause evaluations can provide extremely useful information since they focus on the basic causes of failure.

When root causes are already included in a PRA, the evaluation of their importance involves exactly the same considerations as has been discussed in the preceding chapters. However, the usual PRA does not generally include root cause contributions. We therefore describe in this section how root cause contributions can be included in PRA's along with associated data requirements.

The approach we present incorporates the contributions of root causes to component failure rates, to component repair times, and to common cause probabilities. The contributions are included in a straightforward manner by multiplying probabilities usually obtained in a PRA by appropriate relative root cause fractions. The multiplications are done at the tail end of the quantifications and hence no basic PRA models need to be changed.

5.1 Incorporating Root Cause Contributions to Component Failure Rates

We assume the usual PRA models as described in (3). Consider a given component failure mode and let its failure rate be denoted by λ. The failure rate can either be a cyclic or hourly rate. Let

$$r_i = \text{the fraction of failures for the given component failure mode which are due to root cause } i \qquad (139)$$

The quantity r_i can be termed the root cause failure fraction, or simply the root cause fraction.

Each different component failure rate will have its own unique set of root cause fractions. The root cause fraction r_i for a given component failure mode can be estimated as

$$r_i = \frac{n_i}{n} \tag{140}$$

where

n = the total number of failures (the sample size) which was used to categorize root causes (141)

and

n_i = the number of failures, out of n, which are associated with root cause i. (142)

The root cause fractions are defined to be mutually exclusive and exhaustive so that

$$\sum_{i=1}^{K} r_i = 1 \tag{143}$$

For example, to satisfy the above equation, one category can be defined as "other". The root causes and corresponding root cause fractions can be defined at different levels, from general categorizations to detailed categorizations, to give different levels of root cause information.

The component failure rate λ_i due to root cause i can then be expressed as

λ_i = the component failure rate due to root cause i (144)

$= \lambda r_i$ (145)

Let q_i^f be the component unavailability due to the root cause i contribution to the failure rate:

q_i^f = the component unavailability due to the root cause i contribution to the failure rate (146)

The superscript "f" on q_i^f denotes that the unavailability incorporates the root cause contributions to failure. We shall simplify this notation shortly. The root cause unavailability q_i^f is computed with the usual PRA formulas but using λ_i instead of λ for the component failure rate. From Equation (145), q_i^f is however more simply computed by multiplying the usual component failure unavailability determined in a PRA by r_i:

$$q_i^f = q\, r_i \tag{147}$$

where

q = the usual component unavailability computed in a PRA due to failure from any root cause* (148)

5.2 Incorporating Root Cause Contributions to Component Downtimes

The component unavailability q_i^f incorporates the effects of root causes on component failures but it does not incorporate the potential effects of root causes on the component repair time, or failure downtime, of the component. If the downtime is modeled as being independent of the root cause then there will be no root cause effects on the downtime. The root cause, for example, will have no effects on the downtime when repairs or corrective maintenances are modeled as using the total allowed outage time regardless of the root cause. When there are no root cause effects on the downtime, then q_i defined by Equation (146) will incorporate all the major effects of root causes on the component unavailability.

When root causes are modeled as having an effect on the downtime, then the component unavailability can be simply modified to also incorporate this effect. Let s_i be the ratio of the downtime for root cause i over the average downtime:

$$s_i = \frac{d_i}{\bar{d}} \tag{149}$$

where

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* A component failure unavailability is any component unavailability contribution containing the component failure rate as a factor.

d_i = the component failure downtime for root cause i (150)

and

d = the average component failure downtime for all root causes (151)

The ratio s_i can be termed the root cause downtime fraction. Note that the ratio s_i can be smaller or larger than 1.

Let q_i^d be the component unavailability incorporating the root cause effects on the failure downtime:

q_i^d = the component unavailability considering the effects of root cause i on the failure downtime. (152)

The superscript "d" on q_i^d denotes the unavailability incorporates the root cause contribution to the component failure downtime. Again this notation will be shortly simplified, however, it is important to identify the separate effects of the root causes. Only the root cause's effects on the downtime are considered in q_i^d and not its effects on the failure rate. By the definition of the root cause downtime fraction s_i, the unavailability q_i^d is simply obtained by multiplying the usual PRA component failure unavailability q by s_i

$$q_i^d = q\, s_i \tag{153}$$

5.3 Incorporating All Root Cause Contributions

The unavailability contributions from a root cause to both the failure rate and the downtime can be incorporated by again simple multiplications. Let q_i^{fd} be the component unavailability due to the root cause i contribution to both the failure rate and downtime:

q_i^{fd} = the component unavailability due to root cause i considering effects on both the failure rate and failure downtime. (154)

The root cause component unavailability q_i^{fd} thus incorporates all the major effects of the ith root cause.

By our definitions of the root cause fractions r_i and s_i, we can simply calculate q_i^{fd} as

$$q_i^{fd} = qr_i \, s_i \tag{155}$$

Note that we also have the relations,

$$q_i^{fd} = q_i^f \, s_i \tag{156}$$

and

$$q_i^{fd} = q_i^d \, r_i \tag{157}$$

The above equations are examples of separable effects models since we have separated the failure rate and downtime effects of the root cause. Separable effects models are very useful for application purposes since the separate effects are identified and straightforward calculations are only involved.

We shall now simplify the notations. Since q_i^{fd} incorporates all the major effects of the ith root cause we shall drop the superscripts and simply use q_i;

$$q_i = q_i^{fd} \tag{158}$$

$$= \text{the component unavailability due to root cause } i \tag{159}$$

We shall also denote the product $r_i s_i$ of root cause fractions as the ith root cause unavailability fraction f_i

$$f_i = r_i s_i \tag{160}$$

We can also simply call f_i the ith root cause fraction when there is no confusion with the failure or downtime fractions.

Using the above notation, we then simply have

$$q_i = q\, f_i \tag{161}$$

Note that where the component downtime is not affected by the root cause, then $s_i = 1$ and then $f_i = r_i$, the root cause fraction to the failure rate. We also do not decompose any unavailability contribution which is not affected by root cause considerations, such as a test downtime contribution, but will simply leave it as a constant*. The above equation thus allows the root cause contributions to be simply calculated for the different various applicable situations.

We have one final set of component unavailability relationships. The total component failure unavailability q is simply the sum of the individual root cause contributions

$$q = \sum_{i=1}^{K} q_i \tag{162}$$

where again there are K identified root causes. Substituting Equation (161) into (162) we have

$$\sum_{i=1}^{K} f_i = 1 \tag{163}$$

and hence the unavailability fractions sum to one (even if there are some downtime fractions s_i which are greater than 1). By Equation (163), each f_i is thus the relative contribution of the root cause to the component unavailability:

f_i = the contribution importance of root cause i to the component unavailability. (164)

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* We could also assign $f_i = \frac{1}{K}$ for all i for these unaffected contributions to denote that the contribution equally applies to all root causes.

Finally substituting $f_i = r_i s_i$ and $s_i = d_i/d$ in Equation (163) we also obtain

$$d = \sum_{i=1}^{K} r_i d_i \qquad (165)$$

which is the definition of the average downtime in terms of r_i and d_i.

5.4 Contributions of Root Causes to System Unavailability and Core Melt Frequency

Using the previous equations, we can straightforwardly obtain the contributions of root causes to system unavailability, core melt frequency, and any other risk characteristic. We shall consider only independent component failures here and we will show how the results can be simply modified for common cause failures in the next section. We assume each component has the same root cause categories, say a total of K of them. For certain of the categories f_i can be zero.

Let

C_i = the contribution of root cause i to core melt frequency (or to system unavailability or to any other risk characteristic). (166)

Then C_i can be written generally as

$$C_i = \sum_{m=1}^{N} Q_{m_i} \qquad (167)$$

where

Q_{m_i} = the root cause contribution to minimal cut set m. (168)

Equation (167) computes the root cause contribution as the sum of the minimal cut set contributions. Equation (167) is based on the rare event approximation standardly used in PRAs.

To compute Q_{m_i} for a given minimal cut set, the root cause decomposition $\sum_{i=1}^{K} q_i$ can be substituted for each pertinent component failure unavailability q and terms involving root cause i can be collected after multiplying the root cause unavailabilities. Instead of determining the contribution Q_{m_i} in terms of q_i, the relationship $q_i = qf_i$ can be used and the contribution Q_{m_i} can be expressed in terms of f_i.

This second alternative is equivalent to substituting $q = q \sum_{i=1}^{K} f_i$, multiplying the sums $\sum_{i=1}^{K} f_i$ for the different failure component unavailabilities in the cut set, and then collecting all terms involving f_i. Instead of doing this we can use standard factoring formulas for products of sums and simply write down the results for Q_{m_i}. These results can also be directly obtained by treating f_i as a root cause probability and considering Q_{m_i} as the probability that the ith root cause is the cause of any of the component failures.

From the above considerations, for a single component failure unavailability in the minimal cut set, the contribution Q_{1_i} is simply given by

$$Q_{1_i} = Q_1 \, f_i \tag{169}$$

where

$$Q_1 = \text{the total minimal cut set contribution} \tag{170}$$

The minimal cut set contribution Q_1 is the quantity standardly calculated in PRAs.

For two component failure unavailabilities in the minimal cut set, the contribution Q_{2_i} is given by

$$Q_{2_i} = Q_2 \, (f_{1_i} + f_{2_i} - f_{1_i} f_{2_i}) \tag{171}$$

where

$$f_{1_i} = \text{the ith root cause fraction for component 1} \tag{172}$$

$$f_{2_i} = \text{the ith root cause fraction for component 2} \tag{173}$$

and

$$Q_2 = \text{the total minimal cut set contribution.} \tag{174}$$

The quantity Q_{2_i} is thus simply the usual minimal cut set contribution Q_2 multiplied by the factor $f_{1_i} + f_{2_i} - f_{1_i} f_{2_i}$. This second factor can be interpreted as the probability that at least one component is down due to root cause i.

For three component failure unavailabilities in the minimal cut set, the factored expression is:

$$Q_{3_i} = Q_3(f_{1_i} + f_{2_i} + f_{3_i} - f_{1_i}f_{2_i} - f_{1_i}f_{3_i} - f_{2_i}f_{3_i} + f_{1_i}f_{2_i}f_{3_i}) \quad (175)$$

The second factor on the right hand side of Equation (175) can be interpreted as the probability that at least one component is down due to root cause i.

The general formula for Q_{m_i} is

$$Q_{m_i} = Q_m C_{m_i} \quad (176)$$

where the root cause cut set factor C_{m_i} is

$$C_{m_i} = \sum_{i=1}^{N} f_{k_i} - \sum_{j>k}^{N} f_{k_i} f_{j_i} + (-1)^{N-1} f_{1_i} f_{2_i} \ldots f_{N_i} \quad (177)$$

The equation for C_{m_i} is the standard equation for the ith term in a product of sums. It is also the standard equation for the probability of a union of events (of any component being down due to the ith root cause).

The above formulas thus allow each usual minimal cut set contribution to be extended to include pertinent root cause contributions by simply multiplying by an appropriate factor. Consequently, PRAs can be simply extended to give the root cause contributions which are important for many applications.

Once the root cause contributions, C_i, are obtained by summing over the minimal cut set terms then they can be displayed as part of the PRA information. The normalized root cause contributions, $\bar{C}_i$, defined as

$$\bar{C}_i = \frac{C_i}{\sum_{i=1}^{K} C_i} \quad (178)$$

can also be displayed. The root cause contributions C_i and $\tilde{C}_i$ give the contribution of the ith root cause to the particular risk characteristic of interest. These root cause contributions are similar in nature to the Fussell-Vesely importances and answer the question "How much of the risk is contributed by root cause i." Using the above approaches, the root cause contributions can be obtained to expected health and economic risks, to core melt frequency, to system unavailability, and to any other risk characteristic. These root cause contributions significantly increase the information which is provided by a PRA.

5.5 Incorporating Root Cause Contributions to Common Cause Probabilities

The previous equations for the determination of root cause contributions to risk can be simply modified to incorporate common cause considerations. Consider again specific component failure modes. Let v_i be the ratio of the common cause probability for root cause i over the average common cause probability for all root causes:

$$v_i = \frac{p_i}{p} \tag{179}$$

where

$$p_i = \text{the common cause probability for root cause i} \tag{180}$$

and

$$p = \text{the average common cause probability for all root causes.} \tag{181}$$

The common cause probability P_i is the probability that one or more additional failures occur given root cause i caused one component to fail. The common cause ratio v_i can be estimated as

$$v_i = \frac{\dfrac{n_{ic}}{n_i}}{\dfrac{n_c}{n}} \tag{182}$$

where

n_{ic} = the number of common cause failures involving root cause i (183)

n_i = the total number of root cause i failures (184)

n_c = the total number of common cause failures for all root causes (185)

n = the total number of failures (186)

The above failure counts are with regard to an observed sample. Since v_i is a relative value, like all the other root cause fractions, the sample does not need to be complete but does need to be representative.

The common cause ratio v_i can also be interpreted as the ratio of the beta factor β_1 for root cause i over the beta factor for all root causes. The common cause ratio v_i can furthermore be extended to consider common cause failures which involve exactly 1 additional failure, those which involve exactly 2 additional failures, etc. For this extension, there would be a v_i for each number of failures considered, and the estimation of v_i would have formulas similar to Equations (182) - (186) where now n_{ic} and n_c involve a specific number of failures. Most PRAs do not treat this detail and the above formulas, Equations (182) - (186), are generally sufficient.

The common cause ratios v_i can be used to straightforwardly modify the root cause contributions of the previous section to incorporate common cause failure effects. Consider a minimal cut set which contains a common cause contribution. Let the modified root cause fraction f_i' be defined as

$$f_i' = r_i s_i v_i \quad (187)$$

$$= f_i \, v_i \quad (188)$$

The modified root cause fraction f_i' thus simply is the product of the individual root cause fractions r_i, s_i, and v_i for the ith root cause--now including the common cause fraction v_i. The prime "'" in f_i' denotes that the

root cause fraction f_i has been modified (multiplied by v_i) to incorporate common cause effects.

The modified root cause fraction f_i' can now be used in place of f_i in the formulas given in the previous section. For example, for a minimal cut set of one common cause failure, the root cause minimal cut set contribution Q_{1_i} is

$$Q_{1_i} = Q_i f_i' \tag{189}$$

Note that the one common cause failure can affect any number of individual components. For a minimal cut set containing one common cause failure and one independent failure, the minimal cut set contribution Q_{2_i} is

$$Q_{2_i} = Q_2 (f_{1_i}' + f_{2_i} - f_{1_i}' f_{2_i}) \tag{190}$$

The formulas in the preceding section can consequently be used with these straightforward modifications to also incorporate common cause effects of root causes.

6. Uncertainty Considerations in Evaluating Importances

This last section discusses uncertainty considerations in evaluating and utilizing risk importances, particularly quantitative risk importances. PRA's and other types of risk analyses which are used to evaluate risk importances have uncertainties which are associated with assumptions, models, and data. Therefore risk importances which are evaluated from these analyses will have associated uncertainties. Sometimes these uncertainties can be significant. Even with their associated uncertainties, the risk importances can still provide meaningful information if properly interpreted and utilized.

6.1 Contributions to Uncertainties in Risk Importances

The discussion here is centered on quantitative importances although the considerations also generally apply to qualitative importances. As

described in Section 4.1, quantitative risk importances can be generally expressed as a difference of the risks with the factor in and with the factor out. For example, the importance of a detrimental factor can be written as:

The importance of a detrimental factor	=	The risk with the factor in	-	The risk with the factor out	(191)

The importance of a beneficial factor is similarly expressed with the terms interchanged on the right hand side.

Because the importance involves a risk difference, if the risk is expressed as an additive sum of contributions, then only those contributions affected by the factor will remain when the difference is taken. In terms of the minimal cut set contributions in a PRA, the risk difference is thus determined only by those minimal cut sets affected by the factor:

The importance of a detrimental or beneficial factor	=	The sum of the minimal cut set contributions affected by the factor	(192)

The above equation applies to all the various risk measures which can be used.

In Equation (192) the minimal cut set contributions affected by the factor can be expressed as the difference between the affected minimal cut sets with the factor in and the affected minimal cut sets with the factor out. For a detrimental factor, Equation (192) can thus be re-expressed as:

The importance of a detrimental factor	=	The affected minimal cut set contributions with the factor in	(193)
	-	The affected minimal cut set contributions with the factor out	

For a beneficial factor the terms on the right hand side would simply be interchanged.

Because the risk importance is determined only by the affected minimal cut sets, the uncertainty in the risk importance is determined only by the uncertainties in these minimal cut sets. This uncertainty relationship can be expressed as:

The uncertainty in the risk importance	=	The uncertainty in the affected minimal cut sets contributing to the importance	(194)

The above relationship is very useful for evaluating the uncertainties in the risk importance since only the affected minimal cut sets need to be evaluated for the uncertainty contributions.

6.2 Procedures for Evaluating the Uncertainty in the Risk Importance

Because the risk importance is determined by the affected minimal cut set contributions, standard techniques, such as described in the PRA Procedures Guide (3), can be used for estimating the uncertainty in the risk importance. The problem is similar to estimating the uncertainty in the risk measure itself (e.g., in the core melt frequency) except that the complexity of the evaluations is reduced.

Since standard techniques can be used to evaluate the risk importance uncertainty, these techniques will not be discussed here. However, two special considerations are worth noting. If the risk importance is essentially determined by one minimal cut set, then the uncertainty in the risk importance is the minimal cut set uncertainty. Since the minimal cut contribution is simply a product of the component contributions, the uncertainty evaluation can at times be explicitly performed without detailed computer code analyses required.

With regard to the second point, when two or more risk importances are evaluated, then it is desired to identify those risk importances which are significantly different from one another accounting for uncertainties. A straightforward approach is to estimate an error spread for each risk importance and declare those importances to be significantly different whose error spreads do not overlap. This approach is a gross approach and does not necessarily account for the statistical dependencies among the minimal cut sets. However it is generally conservative and can be useful as a first approximation.

For more precise evaluations, the dependencies among the minimal cut sets can be bounded using positive dependency approaches[(8)]. Alternatively,

the uncertainties in the differences or ratios of the importances can be evaluated through simulation or other propagation techniques. This involves, for example, evaluating the probability distribution of $\Delta R_1/\Delta R_2$ where ΔR_1 and ΔR_2 are two risk importances which are compared. The two importances would be declared significantly different if the probability that $\Delta R_1/\Delta R_2$ is greater than some resolution value, such as a factor of 10, is sufficiently large, such as being greater than 90 percent.

6.3 General Guidelines on Sizes of Risk Importance Uncertainties

As a final section in this report, some guidelines can be given on the general sizes of risk importance uncertainties if current PRA's are used for the importance evaluations. These guidelines are based on sizes of uncertainties in present PRA's (see for example (9)).

Sizes of uncertainties on individual component unavailability contributions to a minimal cut set range from an error factor of 3 to an error factor of 10. The error factor is defined as the ratio of the approximate 95 percent upper bound to the central estimate. The error factors are smaller for active components (e.g., motor operated valves and pumps) and are larger for passive components (e.g., wires and piping).

Based on current PRA's, individual minimal cut sets which consist of 1 to 3 components therefore generally have error factors of about 10. Thus risk importances which are determined by these types of minimal cut sets will have error factors of about 10. As the number of contributing minimal cut sets increase, the error factor tends to decrease. Estimated core melt frequencies for example, which are determined by about 5 or more minimal cut sets, have error factors ranging from about 3 to about 6.

Based on the above results, a general guideline is to associate a factor of 3 to 10 uncertainty with risk importances which are determined by minimal cut sets of 1 to 3 components. The smaller error factor would be associated with larger numbers of minimal cut sets contributing (e.g., > 5). Also, these risk importances can be declared to be different if they differ by more than a factor of 10. For better approximations and other cases, uncertainty evaluations will need to be carried out.

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This report presents approaches for utilizing Probabilistic Risk Analysis (PRA) to determine risk importances. PRAs can be used to identify the importances of risk contributors or proposed changes to designs or operations. The objective of this report is to serve as a handbook and guide in evaluating and applying risk importances. The utilization of both qualitative risk importances and quantitative risk importances is described in this report. Qualitative risk importances are based on the logic models in the PRA, while quantitative risk importances are based on the quantitative results of the PRA. Both types of importances are among the most robust and meaningful information a PRA can provide.

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