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I am submitting herewith a thesis written by Carroll L. Cate entitled "A Method for Quantitative Evaluation of Common Cause Failures in System Reliability Analyses." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Engineering, with a major in Nuclear Engineering.

J.B. Fussell, Major Professor

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# A METHOD FOR QUANTITATIVE EVALUATION OF COMMON CAUSE FAILURES IN SYSTEM RELIABILITY ANALYSES

A Thesis

Presented for the

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Degree

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## ABSTRACT

This thesis discusses a methodology for including the probabilistic effects of potential common cause failure in the quantitative analysis of a system reliability analysis. The treatment of potential common cause failure identified by various criteria is examined. In order to illustrate the methodology, an analysis of the Plant Protection System of the proposed Clinch River Breeder Reactor Plant is presented.

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# CHAPTER I

## INTRODUCTION TO THE QUANTIFICATION OF POTENTIAL COMMON CAUSE FAILURES

Reliability engineering is that discipline which strives to increase the probability that a system will function under specified conditions, without failure, for a specified period of time. Reliability engineering offers a methodology by which systems may be designed to achieve, within the bounds of engineering capabilities, the requirements of optimum safety, plant availability, cost and complexity.[1] Steps in a system reliability analysis[2] include:

1. System definition.[3]
2. System logic model construction.[4, 5]
3. Qualitative analysis.[6]
4. Common cause analysis.[7]
5. Quantitative analysis.[8, 9]
6. Formulation of conclusions and recommendations.
7. Final documentation.

This thesis presents a method for including the probabilistic effects of potential common cause failure in the quantitative analysis.

Recent developments have been made in the qualitative common cause analysis at The University of Tennessee and the Idaho National Engineering Laboratory (INEL). These developments extend the methodology of the Reactor Safety Study (WASH-1400).[10] Two computer programs, BACFIRE (see Appendix I) developed at The University of Tennessee and

COMCAN[11] developed at INEL, aid in qualitative common cause analysis. These computer programs are compatible with the other computer programs used in reliability engineering that incorporate the cut set methodology. A minimal cut set is a smallest collection of basic events (i.e., component failures), such that if all these basic events exist at the same time, then the TOP event, that is, the system failure being analyzed, exists.[9]

In most cases the qualitative analysis computer aids[12-14] are used to identify the minimal cut sets of the system logic model. The logic model is a logical development of an event to its causes.[4] The "fault tree" used in fault tree analysis is a logic model. Logic models constructed for a particular TOP event are developed to failures of individual components within the system being analyzed. The minimal cut sets will identify the sets of component failures that lead to the TOP event.

Coupled component malfunctions often contribute to system failure. Strictly, a common cause failure is <u>any</u> multiple component malfunction that results from a single event. However, the present computer-aided, qualitative common cause failure analysis methods only determine those potential common cause failures which result in system failure. The minimal cut sets are examined for common qualitative failure characteristics[7, 11] (Appendix I, Section I-3) which couple component failures.[1] A minimal cut set in which all the components implied by the basic events share a

---

[1]Actually, all the minimal cut sets do not have to be determined. A synthesis procedure may be used to obtain system results just as if all these cut sets had been determined. See references 15 and 16 for details.

common qualitative failure characteristic is a common cause candidate. The complete list of component minimal cut sets (minimal cut sets which consist solely of component failures)[2] must be examined to determine the common cause candidates for the system being analyzed. The largest minimal cut set cannot be discarded before determining the common qualitative failure characteristics. The common link implies a single event which may cause the TOP event.

The objective of the quantitative system reliability analysis is to obtain a time-dependent quantitative representation of the probabilistic reliability characteristics of a particular system failure (TOP event).[9] Existing methodologies can be used to predict the quantitative reliability characteristics of a TOP event from the minimal cut sets and component reliability characteristics.[12, 17] These methodologies were developed assuming independent basic events for the analysis. The probability of independent component failures leading to the TOP event is extremely low in present day nuclear system design because of redundancy and improved component characteristics. Yet, there is room for system improvement in the area of coupled component failures. These common cause failures need to be determined, and the effect of the common cause failure event must be included with the independent component

---

[2] In this context, "component" refers to the limit of resolution (i.e., the basic events) of the system logic model. Basic events are malfunctions of hardware components of a system or system "software" such as operator or computer codes which are required for system operation. The explicit inclusion of caused failure, sometimes called secondary failures (7, Appendix I-2-i, page 38), for components in the logic model is not required for the approach presented here. However, cut sets which are determined from fault trees that are developed with the secondary failures can also be analyzed by the qualitative common cause analysis methodology.

failures to predict the reliability characteristics of the TOP event.

The purpose of this thesis is to delineate a procedure for including the probabilistic effects of potential common cause failures with those of the component minimal cut sets in the quantitative reliability analysis. Other methods have been developed to represent common cause failures quantitatively.[18-21] However, these other methods result in more complex expressions for the quantitative reliability characteristics of the minimal cut set. These more complex expressions for the reliability characteristics are not yet programmed to fit with existing computer-aided quantitative methods. The method presented here predicts system reliability characteristics using existing computer-aided methods and by including the effects of potential common cause failure and the independent failure of the components in a minimal cut set separately. In addition, these existing quantitative methods do not interface with existing qualitative methods for common cause failure analysis.

The reliability characteristics that may be predicted for the TOP event by the quantitative analysis include the system availability, reliability, expected number of failures and failure-rate. These terms are defined in Reference (2) as follows:

1. Availability: The probability that the system failure does not exist at some specified time in the future.

2. Reliability: The probability that the system has experienced no failures during a specified time interval.

3. Expected number of failures: The statistically expected number of failures during a specified time interval.

4. Failure-rate $\lambda$: Defined such that $\lambda dt$ is the probability of failure during t to t + dt, given no failures before time t.

A thorough discussion of the significance of each of these reliability characteristics can also be found in Reference 2.

The potential common cause failures that are used in the quantitative analysis are usually determined after searching various categories of qualitative failure characteristics in the qualitative common cause analysis. Some of the categories used to identify common cause failures are:[22-24]

1. Functional deficiency.
2. Design and manufacturing deficiencies.
3. Operating or maintenance deficiencies.
4. External normal environmental factors.
5. Natural phenomena.

Another scheme for categorizing common cause failure is (1) cause of secondary failure of the basic events and (2) special conditions which couple the basic events.[7, 11, Appendix I, page 38] For this thesis, cause of secondary failure, representing "external normal environmental factors" and "natural phenomena," and special conditions which include the other categories for common cause failure, will be used. Each of these two categories for common cause failure will be discussed for the quantification process. A sample of the qualitative failure characteristics which may be important for the special condition category are listed in Table 1. Some of those qualitative failure characteristics identified in the cause of secondary failure category are listed in Table 2.

The potential common cause failure, either cause of secondary failure or special condition, and the associated probabilistic failure data is the information required for the quantification process. The

TABLE 1

SPECIAL CONDITIONS RESULTING IN DEPENDENCE BETWEEN COMPONENTS

| Common Link | Example Situations |
|---|---|
| Calibration | Misprinted calibration instructions. |
| Energy flow paths | Located in same electrical circuit, located in same hydraulic loop. |
| Energy source | Same power supply, common drive shaft. |
| Installation | Same subcontractor, same crew. |
| Maintenance | Inadequately trained person, incorrect procedure. |
| Manufacturer | Repeated fabrication error, inferior material. |
| Operator | Faulty operation procedure, disabled or overstressed operator. |
| Similar parts | Important in the case of minimal cut sets which contain only pumps, or only valves. |
| Test procedure | Faulty test procedure, incomplete testing. |

TABLE 2

CAUSES OF SECONDARY FAILURE RESULTING IN DEPENDENCE BETWEEN COMPONENTS

| Generic Failure Cause | Example Source |
|---|---|
| Biological hazards | Poisonous gases, explosions, missiles. |
| Carbonization | Oil in liquid sodium. |
| Conducting medium | Moisture, conducting gases. |
| Corrosion | Acid spills, cleaning agent residue, water. |
| Electromagnetic interference | Rotating electrical machinery, lightening, transmission lines, welding equipment. |
| Grit | Airborne dust, failed filter systems. |
| Impact | Pipe whip, water hammer, missiles, earthquake, structural failure. |
| Moisture | Steam leak, valve leak. |
| Over current | Short circuit. |
| Over voltage | Power surge. |
| Pressure | Explosion, pump overspeed, flow blockage. |
| Radiation | Neutron sources. |
| Stress | Thermal stress at welds, temperature transients. |

causes of secondary failure and the special conditions pertinent to the system failure are determined from the common cause candidates. Standard quantitative analyses[12, 17] can then be performed considering the component minimal cut sets, causes of secondary failure, and special conditions.

Considering only common cause candidates limits the analysis to only those common cause failures which can directly cause the TOP event. The methodology presented here is easily generalized. Those common cause failures that cause some but not all basic events in a minimal cut set are determined. The common cause failure event then replaces the coupled basic events. The new cut set consists of the remaining basic events and the common cause failure and is added to the list of component minimal cut sets. The complete list of cut sets is then used in the quantification process. Preparation of the quantitative failure data for the common cause failure event is the same as the procedure described in this thesis. The procedure for determining potential common cause failure events for this generalized case is not yet programmed for a computer. This extension of the methodology results in a more tedious and somewhat more unmanageable analysis with marginal returns in most cases.

Another limitation in the analysis is the lack of quantitative data available. There is no data bank with complete quantitative failure data available for common cause failure at this time.

The results of the qualitative common cause analysis that are used for the quantification process are discussed in the next chapter. The quantitative data that are needed for the potential common cause

failure are outlined in Chapter III. Chapter IV identifies the available computer aids which can be used for quantitative analysis including the potential common cause failure. An example of the methodology which is presented in this thesis is given on a Clinch River Breeder Reactor Project (CRBRP) system in Chapter V. The concluding comments on the quantification of potential common cause failure are then presented in Chapter VI.

# CHAPTER II

## PREPARING THE RESULTS OF A QUALITATIVE COMMON CAUSE ANALYSIS FOR THE QUANTIFICATION PROCESS

The realization that common cause failures always fail the system by inducing failure in the system components simplifies the approach to common cause failure analysis that is presented here. References 15 and 16 elaborate on some of the ramifications of this observation. The qualitative analysis results in minimal cut sets. The common cause analysis results in common cause candidates. The quantitative analysis predicts TOP event reliability characteristics[2] from independent basic events. The methodology for including the minimal cut sets in the quantitative analysis is established.[9] In order to include the common cause candidates, independent basic events must be determined to represent common cause failure in the quantification process. The quantitative failure characteristics of a common cause candidate can be broken into the quantitative failure characteristics of the independent failure of all components implied by the common cause candidate, and the quantitative failure characteristics of the potential common cause failures.[18-21] For a common cause candidate, each common qualitative failure characteristic is identified for all basic events in a minimal cut set. Each common qualitative failure characteristic is represented by one event.

For this analysis, each special condition and each cause of secondary failure identified in a separate domain is represented by a common cause cut set. A common cause cut set is a one-event cut set

that represents the quantitative characteristics of the potential common cause (single) failure for predicting the TOP event reliability characteristics. The component minimal cut sets and the common cause cut sets used in the quantitative analysis are assumed to represent the TOP event adequately to predict system reliability characteristics.

The quantitative data used to predict the TOP event reliability characteristics from the minimal cut sets are the component failure characteristics. Component reliability characteristics are completely described by their time-dependent failure-rate (hazard-rate), $\lambda(t)$, and their time-dependent repair-rate, $\mu(t)$.[2] The quantitative data used to predict the TOP event reliability characteristics from the common cause cut sets are associated with the cause of secondary failure or the special condition. First, consider the common cause cut set which represents a common special condition. Special conditions such as manufacturer and calibration are examples (see Table 1, page 6). The common special condition introduces failure into the system with an occurrence probability, Pr.(failure). This is to say that there is a certain contribution to the system reliability characteristics by the special condition. This probabilistic effect on the system is represented by the addition of the one-event cut set for the quantification process.

Next, look at the common cause cut set which represents a common cause of secondary failure. Some mechanisms for secondary failure may similarly introduce failure into the system with a constant probability. However, most mechanisms for secondary failure (see Table 2, page 7) are described better by an occurrence-rate, L(t). Large machinery such as

compressors or pumps is a typical source of vibration. Vibration may accompany normal operation of the machinery, or it may be intermittent and depend on other stimuli such as changes in load. The vibration may only occur during startup or shutdown of the machinery. In any case, an occurrence-rate can be determined for the potential cause of secondary failure.

A cause of secondary failure introduces failures into a system at a rate that is proportional to the occurrence-rate of the mechanism for secondary failure. All components will not fail at each occurrence of a cause of secondary failure. The occurrence-rate of the mechanism for secondary failure, $L(t)$, must be weighted by the fraction of occurrences, $S$, that will actually cause cut set failure to obtain the failure-rate, $\lambda(t)$, associated with the cause of secondary failure. This is to say

$$\lambda(t) = S \cdot L(t).$$

The repair-rate, $\mu(t)$, is unique to the potential common cause failure and must represent repair of both the common cause candidate and the failure cause.

# CHAPTER III

## DISCUSSION ON DETERMINING QUANTITATIVE DATA FOR POTENTIAL COMMON CAUSE FAILURE

There is no data bank with complete quantitative failure data available for common cause failure. Therefore, the analyst is responsible for determining all quantitative data for each of the common cause cut sets. The probabilistic effects of the common cause cut sets along with those of the component minimal cut sets are used in the quantitative system reliability analysis. The quantitative system analysis can be used to show compliance with probabilistic design criteria or with safety requirements. However, the difficulty of determining the quantitative common cause failure data hinders the system quantification process.

The quantitative reliability characteristic of a special condition, Pr.(failure), is the probability of the TOP event occurring by that special condition. Many special conditions of Table 1, page 6, are human error. A large percentage of the probability of causing the TOP event assigned the special conditions of operator or operation, test procedure, maintenance, installation, calibration, and even manufacturer is through human error.[25] Even trained and experienced personnel perform misoperation on occasion. Stress, fatigue, and even "routine" influence human performance. However, the quantitative data for system failure brought about by human error is not yet contained in a data bank.[26] The analyst will have to estimate the action or inaction in each instance and assign some value for the Pr.(failure), the special conditions' contribution to the TOP event.

Only one common cause cut set is added for each special condition. For example, if three common cause candidates are identified by special condition "maintenance crew one," then only one common cause cut set (not a common cause cut set for each common cause candidate) is used. "Maintenance crew two" is a different condition from "maintenance crew one"; consequently, if the special condition "maintenance crew two" results in a common cause candidate, then the special condition requires a separate common cause cut set to represent it. The common cause cut set then has Pr.(failure) assigned by the analyst.

The quantitative reliability characteristics of a cause of secondary failure are a time-dependent failure-rate and a time-dependent repair-rate. The cause of secondary failure must be considered in the domain in which it is identified as a potential cause of failure when the reliability characteristics are determined. The particular domain for the failure cause is important because occurrences of the cause of secondary failure are assumed to be independent in each separate domain. Specific causes of secondary failure can be investigated within each domain to aid in determining the occurrence-rate, L(t). Some occurrence-rates may be dominated by failures of other systems or components in the domain. For example, the occurrence-rate for moisture in a room could be dominated by the failure-rate of a steam line passing through it. The occurrence-rate for dust in a controlled atmosphere could be nearly equal to the failure-rate for filters in the air supply system. Secondary pump failure could be dominated by the occurrence of valve chatter which leads to cavitation.

A mechanism for secondary failure may not be known in the same domain as the common cause candidate. However, this does not mean the cause of secondary failure cannot occur. The determination of the occurrence-rate in all instances is presently at the discretion of the analyst.

The occurrence-rate of the cause of secondary failure is only part of the data required to determine the failure-rate of the common cause cut set. The percent of occurrences of the cause of secondary failure, S, which result in cut set failures must also be considered. The percentage of occurrences which cause failure is a basic event characteristic. A scheme is recommended to rank the sensitivity of a basic event to each of its susceptibilities on a scale from 0 to 9. The sensitivity rank corresponds to the percentage of failures expected from each occurrence of the cause of secondary failure. The sensitivity ranking of basic events to potential causes of failure has been recommended by previous qualitative efforts also.[7, 11, Appendix I, p. 39] A threshold scheme is used for ranking basic event sensitivity. All basic events in a minimal cut set must be above a given set point before the minimal cut set is considered to fail from the cause of secondary failure and is identified as a common cause candidate. If any basic events in the minimal cut set are below the set point, then the minimal cut set is assumed to function properly at each occurrence of the cause of secondary failure. The sensitivity rank is used in the qualitative analysis to reduce the number of common cause candidates the computer-aided methods identify. The percentage of cut set failures per occurrence of the cause of secondary failure will weight the failure cause occurrence-rate to obtain the cut set failure-rate, $\lambda(t)$. This cut set represents the

probabilistic effects of the cause of secondary failure in a particular domain of the failure cause.

The repair-rate, $\mu(t)$, assigned to the common cause cut set must include several factors. The repair of the cause of secondary failure must be made. This could involve the repair of other systems such as the steam lines or the air filters of a previous example. The repair of at least one event in each failed common cause candidate must also be made. Whether these repairs can be made at the same time as the repair of the failure cause must be considered along with other factors which influence repair-rate. The repair-rate for the new cut set is unique for the cause of secondary failure/domain pair. Factors which must be considered in determining the repair-rate are discussed in Reference 9.

Special attention is given to those causes of secondary failure that affect more than one common cause candidate in a given domain. The method of determining the occurrence-rate of the failure cause, L(t), remains the same as described previously. However, all common cause candidates must be considered to determine the percentage of occurrences of the cause of secondary failure, S, that will result in system failure. Only one common cause candidate must fail, and the least sensitive basic event in the common cause candidate is assumed to be the last basic event to occur. The sensitivity ranking of this least sensitive basic event may give the analyst some aid in determining S for the common cause cut set. Only one new common cause cut set is needed to represent each cause of secondary failure/domain pair regardless of the number of common cause candidates identifying it.

# CHAPTER IV

## QUANTITATIVE ANALYSIS USING AVAILABLE COMPUTER-AIDED METHODS

Some of the computer programs which have been developed to aid in the quantitative system reliability analysis are listed in Table 3. These programs are developed to obtain the probabilistic reliability characteristic predictions for a TOP event from the failure and repair characteristics of the basic events and the minimal cut sets. Inputs common to each of these codes are the quantitative reliability characteristics for each basic event in the analysis and the minimal cut sets which are determined for the TOP event. The inclusion of the common cause cut sets requires extending each of these sets of input.

The quantitative data which has been determined for the common cause failure events are appended to the quantitative data for the basic events. The complete list of quantitative failure data for the basic events and the common cause events constitute this portion of the input data.

The one-event common cause cut sets are added to the list of component minimal cut sets. This amended list of cut sets is then assumed to adequately represent the TOP event for the quantitative analysis.

TABLE 3

COMPUTER PROGRAMS TO PREDICT SYSTEM RELIABILITY CHARACTERISTICS FROM MINIMAL CUT SETS AND BASIC EVENT CHARACTERISTICS

| Program | Reference |
|---|---|
| KITT-1 | 12 |
| KITT-2 | 12 |
| SAMPLE | 10 |
| SUPERPOCUS | 17 |

# CHAPTER V

## AN ILLUSTRATION OF COMMON CAUSE QUANTIFICATION USING THE PROPOSED CLINCH RIVER BREEDER REACTOR PLANT

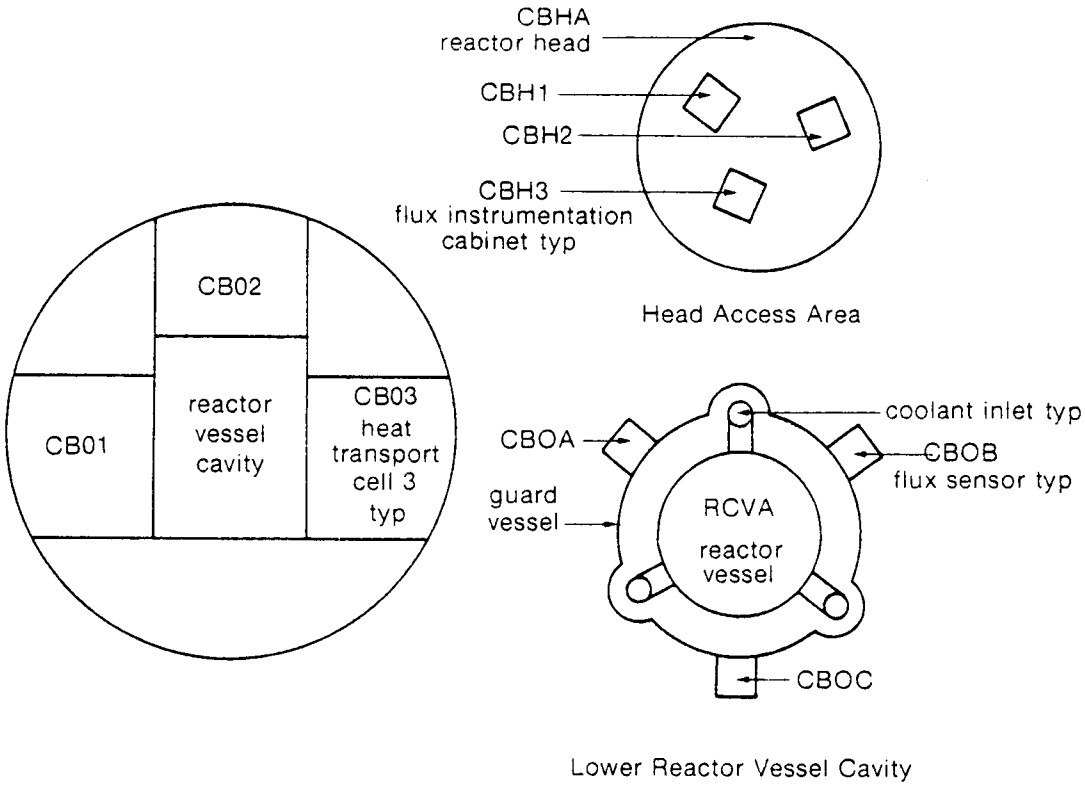
To illustrate the methodology presented in this thesis, the plant protection system (PPS) of the proposed Clinch River Breeder Reactor Plant (CRBRP) is used as an example. The TOP event of the logic model is "Loss of Capability to Shut Down." The limit of resolution of the logic model considers the failure of sensors, transmitters, and control rods, etc., as basic events. Establishing the number of control rods which are required for successful trip was also part of the system definition and logic model construction. Function gates for the two out of three logic are used in the PPS logic model[27] to reduce the complexity of the logic model without forfeiting any representation of the system logic.

The system logic model was analyzed using PREP[12] to determine lower order (i.e., one-, two- and three-event) component minimal cut sets only. Of the estimated $10^{15}$ minimal cut sets total, no lower order component minimal cut sets exist for the TOP event. The common cause analysis was performed using MOCUS[14] and BACFIRE.(Appendix I) Twenty-two hundred common cause candidates were determined.[27] Four potential causes of secondary failure and two special conditions were identified with the common cause candidates. One additional special condition, core displacement, was identified during system definition. The absence of the lower order component minimal cut sets and the relatively small number of common cause candidates are indicative of

a well-designed system. The four causes of secondary failure are impact, electromagnetic interference, temperature, and corrosion. These four causes of secondary failure were identified in 17 domains. Along with core displacement, the special conditions of flux sensor calibration and common manufacturer are also identified. The results of the qualitative common cause failure analysis are represented completely by 20 common cause cut sets. The results of the BACFIRE run for the TOP event are in Appendix II.

Figure 1 is a schematic of the proposed Clinch River Breeder Reactor Plant reactor containment building. The four-character code identifying the physical locations in the containment building is related to the domains of the causes of secondary failure defined by D. P. Wagner.[27] The BACFIRE analysis identified the various domains associated with the four generic causes of secondary failure. Table 4 is a list of the causes of secondary failure and each domain in which it is identified and the special conditions. The associated quantitative failure data subjectively assigned each potential common cause failure is also given. These data were used to illustrate the approach to quantify common cause failure. These data are not expected to be accurate.

The occurrence-rates, L(t), assigned the causes of secondary failure range from 1 in 1,000 years to 1 in 100,000 years ($10^{-7}$/hr. to $10^{-9}$/hr.). Primary heat transport loops are assumed separated from each other for all causes of secondary failure in assigning these occurrence-rates. The fraction of system failures for each occurrence of




| Physical Location | Domains | | | |
|---|---|---|---|---|
| | Impact | Corrosion | Temperature | Electromagnetic Interference |
| CB01 | I001 | A002 | T002 | E002 |
| CB02 | I002 | A003 | T003 | E003 |
| CB03 | I003 | A004 | T004 | E004 |
| CBHA | I013 | A011 | T011 | E005 |
| CBH1 | I013 | A011 | T011 | E005 |
| CBH2 | I013 | A011 | T011 | E005 |
| CBH3 | I013 | A011 | T011 | E005 |
| CBOA | I004 | A001 | T001 | E001 |
| CBOB | I005 | A001 | T001 | E001 |
| CBOC | I006 | A001 | T001 | E001 |
| RCVA | I022 | A052 | T025 | E033 |

Figure 1. CRBRP Reactor Containment Building.

TABLE 4

COMMON CAUSE CUT SETS FOR CRBRP PPS

| Causes | Domain | Occurrences/ Hour L(t) | Failures/ Occurrence S | Failures/ Hour $\lambda(t)$ |
|---|---|---|---|---|
| Impact | I001 | 1 E-8 | 1/100 | 1 E-10 |
| | I002 | 1 E-8 | 1/100 | 1 E-10 |
| | I003 | 1 E-8 | 1/100 | 1 E-10 |
| | I013 | 1 E-8 | 1/100 | 1 E-10 |
| Temperature | T001 | 1 E-7 | 1/1000 | 1 E-10 |
| | T002 | 1 E-7 | 1/1000 | 1 E-10 |
| | T003 | 1 E-7 | 1/1000 | 1 E-10 |
| | T004 | 1 E-7 | 1/1000 | 1 E-10 |
| | T011 | 1 E-7 | 1/1000 | 1 E-10 |
| EM Interference | E002 | 1 E-9 | 1/100 | 1 E-11 |
| | E003 | 1 E-9 | 1/100 | 1 E-11 |
| | E004 | 1 E-9 | 1/100 | 1 E-11 |
| Corrosion (Acid and Oxidation) | A001 | 5 E-9 | 1/100 | 5 E-11 |
| | A002 | 5 E-8 | 1/100 | 5 E-10 |
| | A003 | 5 E-8 | 1/100 | 5 E-10 |
| | A004 | 5 E-8 | 1/100 | 5 E-10 |
| | A011 | 1 E-8 | 1/100 | 1 E-10 |
| Special Conditions | | | | |
| Flux Sensor Calibration | | 1 E-8 | 1/100 | 1 E-10 |
| Core Displacement | | 1 E-8 | 1/10 | 1 E-9 |
| Weston | | | Pr.(failure) = 48 E-7 | |

the causes of secondary failure, S, was chosen to be either 1 in 100 or 1 in 1,000 occurrences. The final failure-rates used for the common cause cut sets ranged from $10^{-10}$/hr. to $10^{-11}$/hr. The quantitative analysis examined the probabilistic reliability characteristics of the TOP event for a period of 1 year. Due to the location of each of these common cause candidates, no repair was allowed during the operating cycle. The repair of each component is also assumed for the start of each operating cycle.

These failure-rates and failure probabilities were used with the 20 common cause cut sets to predict the TOP event reliability characteristics using the SUPERPOCUS[14] computer program. The results of the SUPERPOCUS analysis are in Appendix III. The unavailability, the probability that the system failure does exist at some specified time in the future, is reported here in Figure 2. The TOP event "Loss of Capability to Shut Down" is important only if the system is called on to operate.

In addition to the quantitative analysis, uncertainty bounds were determined for system unavailability for different degrees of confidence in the input data. The SAMPLE[10] computer program was run on the 20 common cause cut sets for two sets of input data. The first set of runs reflects a 90 percent likelihood that the input data are within plus or minus a factor of 10 of the input value. The 90 percent upper bound limit of the system unavailability considering a log normal uncertainty distribution for the input parameter is given in Figure 2. Figure 2 also illustrates a 90 percent upper bound for 90 percent

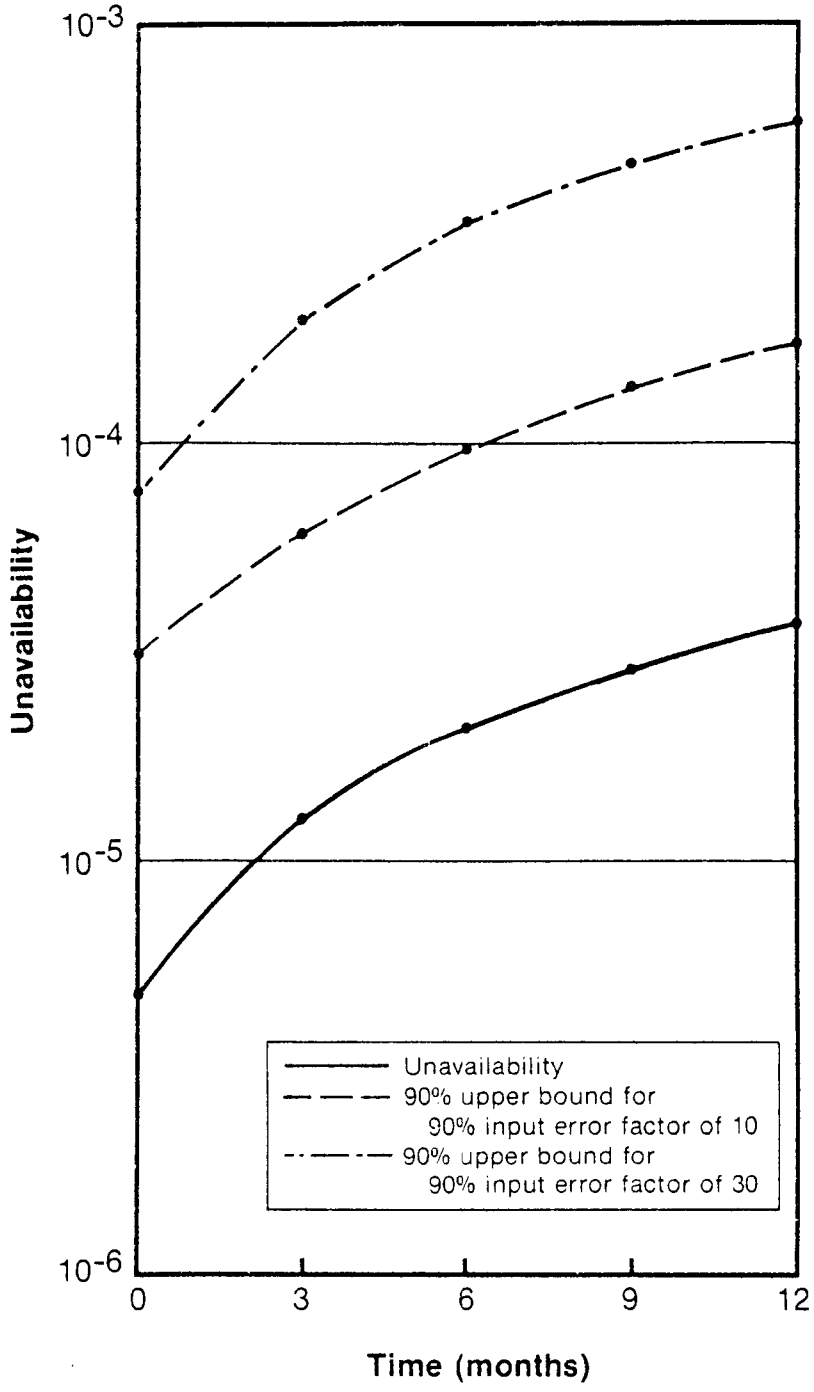



Figure 2. Probability as a Function of Time That the Plant Protection System Will Experience Loss of Capability to Shut Down.

likelihood of input data being between plus or minus a factor of 30 for the log normal model. The output of the SAMPLE[10] runs is in Appendix IV.

The special condition "flux sensor calibration" is examined further. The neutron flux profile changes during the life of the nuclear core requiring recalibration of the sensors. The flux sensors are required to shutdown the reactor during certain hypothetical reactivity transients. The recommendation of adding continuous flux sensor calibration capability has been made.[28] A system which continuously calibrates the sensors from calorimetric measurements of core coolant inlet and outlet temperatures similar to the process used on the High Flux Isotope Reactor at the Oak Ridge National Laboratory is recommended. The quantitative data chosen for the common cause cut set for flux sensor calibration represent incorporation of this suggestion in the plant protective system design.

# CHAPTER VI

## CONCLUDING COMMENTS ON COMMON CAUSE FAILURE ANALYSIS METHODOLOGY

The methodology presented here is a general approach for performing common cause failure analysis. Appropriate steps for a complete common cause failure analysis include:

1. Determine qualitative input data.
    a. Component minimal cut sets.
    b. Component qualitative failure characteristics.
        i. Special conditions.
        ii. Causes of secondary failure.
    c. Component physical location.
    d. Domains of causes of secondary failure.
2. Determine common cause candidates.
3. Determine common cause cut sets.
4. Determine quantitative data for common cause failure.

These steps for a common cause analysis allow determination of potential situations which can lead to system failure and describe a procedure for including the probabilistic effects of these potential situations in the quantitative analysis.

The first step, determining the qualitative input data, is one step in defining the resolution of the analysis. The decision to include all or only part of a basic event's qualitative failure characteristics is a decision of the analyst. The analyst may desire information about only

a select group of qualitative failure characteristics. In addition, the common cause failures are considered on a generic basis for individual components. Once common cause candidates are located, specific causes of multiple component failure can be investigated. The domains which are used in the computer-aided qualitative analysis are also part of defining the resolution of the analysis. By excluding all barriers to a cause of secondary failure in the qualitative common cause analysis, all cut sets which share common qualitative failure characteristics are identified. The inclusion of barriers in the qualitative common cause analysis which do not exist in the system, may preclude the identification of some common cause candidates and indicate the affect on potential common cause failures by the inclusion of these barriers. Changes in design details to include barriers or modify operating procedures or changes in components to use a different component that does not share the common failure characteristic are the two most direct solutions to common cause failure.

The second step also scopes the analysis of common cause failure. By considering only those potential stimulations which could result in system failure, other common cause failures are ignored. The search for specific initiating events does not need to be performed until sets of components and generic causes of their failure are identified. This greatly simplifies the overwhelming task of postulating initiating events and then identifying component failures to see if the TOP event is reached.

The next two steps are necessary for the quantification process. The common cause cut sets that represent the qualitative failure characteristics are added to the component minimal cut sets. A procedure for translating failure event probability distributions into common cause cut set failure distributions is possible by using the sensitivity ranking of the basic events. The sensitivity ranking of the basic events represents a percentage of failures from the failure cause. A probabilistic distribution representing the response of each basic event to a given distribution of each failure characteristic is conceivable. The common cause cut sets and the associated quantitative failure and repair characteristics are used in predicting the reliability characteristics for the TOP event. The results of the quantitative analysis can be used to justify system design changes, to show compliance with probabilistic design criterion, or to show that the system meets with safety requirements.

This procedure also allows the elimination of the assumption of independent component malfunction. The treatment of potential common cause failure as a basic event allows the retention of the assumption of independent basic events necessary in the quantitative analysis. Areas for data collection have also been identified. Qualitative failure characteristics of components and quantitative data for common cause cut sets both need to be investigated to further establish this methodology.

This general procedure for common cause analysis uses existing computer programs throughout the analysis. The use of the computer aids decreases the possibility of ommission in this overwhelming task, and it allows a more thorough and exhaustive treatment of the problem of common cause failure.

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# APPENDIXES

# APPENDIX I

# USER'S MANUAL FOR BACFIRE—A COMPUTER PROGRAM FOR COMMON CAUSE FAILURE ANALYSES

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[1]

## I-1. INTRODUCTION

BACFIRE is a computer program to aid in common cause failure analysis. The program searches among the basic events of a minimal cut set for common potential cause of failure. The potential cause of failure is called a qualitative failure characteristic. A minimal cut set with a common potential cause of failure is called a common cause candidate. An organized search for common cause candidates is called common cause failure analysis. A common cause failure analysis is an essential part of a complete system safety and reliability analysis.

BACFIRE is written in FORTRAN IV for the IBM 360/65 computer. The algorithm searches qualitative failure characteristics (that are part of the program input) of the basic events contained in a minimal cut set to find those characteristics common to all basic events. This search is repeated for all the cut sets input to the program. Common cause failure analysis is thereby performed without inclusion of secondary failures in the system logic model. By using BACFIRE, a common cause failure analysis can be added to an existing system safety and reliability analysis. The associated system logic models need only reflect hardware failures. The hardware minimal cut sets can then be determined by existing methods.[1,2,3] BACFIRE reduces the chance of obtaining erroneous results by error checking of the input and an optional listing of all input. BACFIRE is similar to another common cause failure analysis code called COMCAN.[4]

Included in this appendix are checklists for some generic qualitative failure characteristics. These lists are presented as examples. The analyst can update the lists of generic potential causes of failure as necessary (see Section I-2.i).

Obtaining the qualitative failure characteristics applicable to the components implied by the basic events in the minimal cut sets is time consuming. However, when the information has been collected, it can be stored as library data and used in future analyses.

Section I-2 of this report contains some of the supporting concepts for common cause failure analysis. Section I-3 describes the method for common cause failure analysis which BACFIRE supports. The input to BACFIRE is described in Section I-4. The output from BACFIRE is described in Section I-5.

[3]

## I-2. SUPPORTING CONCEPTS

### i. Primary and Secondary Failures

For the purpose of common cause failure analysis, component malfunctions will be divided into two classes:

A. Primary Failures

B. Secondary Failures

A primary failure is a component malfunction for which the component itself is held responsible. A secondary failure is a component malfunction for which the component itself is not held responsible. Responsibility suggests a sphere of the expected environmental and functional inputs in which a component is expected to function properly. A cause of component malfunction which breaches this sphere is a cause of secondary failure.[5]

Consider a resistor being overheated, causing it to open circuit and a switch which is struct and broken, causing it to open. The resistor transferring open and the switch transferring open are secondary failures. The excessive temperature and the impact which were responsible for the component malfunctions are the causes of secondary failure. The component which experienced the secondary failure in response to the occurrence of the cause of secondary failure is said to be susceptible to that cause of secondary failure. A component may have many different susceptibilities which may give rise to its malfunction. The susceptibilities to the various causes of secondary failure are qualitative failure characteristics of a component malfunction, i.e. a basic event.

ii. Domain

Some causes of secondary failure are confined by barriers. The volume defined by the barriers to the cause of secondary failure is called a domain of the cause of secondary failure. Rooms are common domains for many causes of secondary failure like moisture and temperature. Ventilation systems can spread airborne causes of secondary failure such as dust and gasses to many rooms thereby creating a relatively large domain. Vibration caused by large machinery can affect an entire building. A diagram of all pertinent domains of a cause of secondary failure is called a cause of secondary failure map (see Appendix I-B). For example, a diagram showing all domains of vibration with respect to the basic events is called a vibration map.

iii. Sensitivity Ranking

Components vary in their response to a potential cause of secondary failure. For example, breaker switches vary from light duty to heavy duty. One type may fail if jarred while another will not fail unless it is shaken more violently. Both switches are susceptible to vibration, but the sensitivity to the cause of secondary failure is much less for the latter case. The relative rank of the sensitivity of the component is high for the light duty breaker switch and relatively lower for the heavy duty breaker switch. The rank of a basic event with respect to a specific generic failure cause is expressed as an integer from zero to nine (usually subjectively assigned by the analyst), which reflects the component's tendency to fail from that cause. Zero is the low end of the scale meaning a low tendency to fail, and nine is the high end of the scale reflecting a high degree of susceptibility to the cause of secondary failure.

[5]

## I-3. COMMON CAUSE FAILURE ANALYSIS

The objective of common cause failure analysis is to identify common cause candidates and the qualitative failure characteristics which cause the minimal cut set to be identified as a common cause candidate. For this common cause failure analysis a minimal cut set will be identified as a common cause candidate by either of two criteria.

The first criterion can be met if all the basic events in a minimal cut set are associated by a condition which alone may increase the probability of multiple component malfunction. Some examples of conditions which are checked are listed in Table I-1 and are referred to as "special conditions". An example of a common special condition would be all components implied by the basic events of a minimal cut set having been installed by the same construction crew, or all sharing a common power supply or manufacturer.

The second criterion is met if all the basic events in a minimal cut set are susceptible to the same secondary failure cause and are located in the same domain for that cause of secondary failure. Some examples of the causes of secondary failure which have been used are listed in Table I-2. A susceptibility common to all basic events in a minimal cut set is not alone sufficient to designate the minimal cut set as a common cause candidate. To meet the requirements of the second criterion all the components implied by the basic events in the minimal cut set must be located in the same domain for the common cause of secondary failure. For example, if all the components implied by the basic events in a minimal cut set fail when exposed to excessive heat

TABLE I-1

EXAMPLES OF SPECIAL CONDITIONS FOR THE FIRST CRITERION

| SYMBOL | CONDITION | EXAMPLE SOURCE |
|---|---|---|
| C | Calibration | Misprinted calibration instructions. |
| N | Energy Flow Path | Location in same hydraulic loop. |
| E | Energy Source | Common drive shaft, same power supply. |
| M | Maintenance | Incorrect procedure, inadequately trained personnel, same crew. |
| T | Test Procedure | Faulty test procedures which may affect all components normally tested together. |
| B | Manufacturer | All components constructed by same manufacutrer. |

TABLE I-2

EXAMPLES OF SUSCEPTABILITIES FOR THE SECOND CRITERION

| SYMBOL | SUSCEPTABILITY | EXAMPLE SOURCE |
|---|---|---|
| Category I | | |
| I | Impact | Pipe whip, water hammer, earthquake, structural failure. |
| U | Vibration | Machinery in motion, earthquake. |
| P | Pressure | Explosion, pump overspeed, flow blockage. |
| S | Stress | Thermal stress at welds. |
| T | Temperature | Fire, lighting, collant system faults. |
| C | Current | Short circuit. |
| Category II | | |
| G | Grit | Dust, metal fragments. |
| M | Moisture | Steam leak, valve leak |
| C | Conducting medium | Moisture conducting gasses. |
| R | Radiation damage | Neutron sources, sources of ionizing radiation. |
| Category III | | |
| A | Acid Corrosion | Acid spills, maintenance accident |
| O | Oxidation Corrosion | Unnatural water environment |
| R | Chemical Reaction | Galvanic corrosion, fuel cladding interaction |
| B | Biological Hazard | Poison gasses, explosions. |

and no barrier to heat exists between the components, the cut set is identified as a common cause candidate. In this case the common susceptibility to excessive heat is identified in the output from BACFIRE.

A potential difficulty of common cause failure analysis is the enormous number of secondary failure causes and special conditions. A list of failure characteristics is necessary for the BACFIRE approach in order to maintain continuity throughout the analysis. The list should be of generic causes such that each entry represents a class of secondary failure causes and special conditions. The resolution of these classes should be detailed enough to avoid redundancy and broad enough to maintain physical significance. For example, vibration and impact are preferable entries in the list to pipe whip, water hammer, earthquake, machinery in motion, and other causes. This list can then be organized into categories. One scheme for dividing the list is by the nature of the generic causes, such as chemical or mechanical. To aid in input preparation to BACFIRE, three categories are utilized for the second criterion. Searching for commonalities by BACFIRE is carried out within a category, but not among categories. The qualitative failure characteristics which are checked by the first criterion must be separated from those checked by the second criterion for BACFIRE analysis. These lists (see Tables I-1 and I-2) can be updated to reflect the important susceptibilities and special conditions of the system being analyzed.

BACFIRE searches the qualitative failure characteristics of the basic events contained in the minimal cut set to find those characteristics common to all basic events by either of the two criteria. The minimal cut set that is identified as a common cause candidate is then listed. The

common failure characteristic is also listed with the common cause candidate. BACFIRE determines all other common failure characteristics of the minimal cut set and then continues to the next cut set.

The number of common cause candidates may become larger than desired. If this occurs only the more sensitive common cause candidates may be desired. BACFIRE contains the option of determining only those common cause candidates for which the secondary failure susceptibility exceeds some minimum sensitivity ranking for each event.

By identifying common cause candidates by these criteria, a common cause failure analysis that requires only the hardware minimal cut sets and component qualitative failure characteristics as input is possible. The common cause failure analysis can then be added to an existing system safety and reliability analyses that have produced only hardware minimal cut sets.

The course of the computer analysis is shown in the program flow chart of Figure I-1. After all the data is stored in the libraries (steps one through four), each cut set is read one at a time (step five) and checked for commonalities. The cut set is first checked for common susceptabilities (step seven).

If a common susceptibility is found, the physical location is checked for common domain (step nine). After checking for both conditions of the second criterion, BACFIRE checks the cut set by the first criterion (step ten). The program then checks to determine if all minimal cut sets have been examined (step eleven). When all common cause candidates have been determined, the results are printed (step twelve) and the analysis is completed.

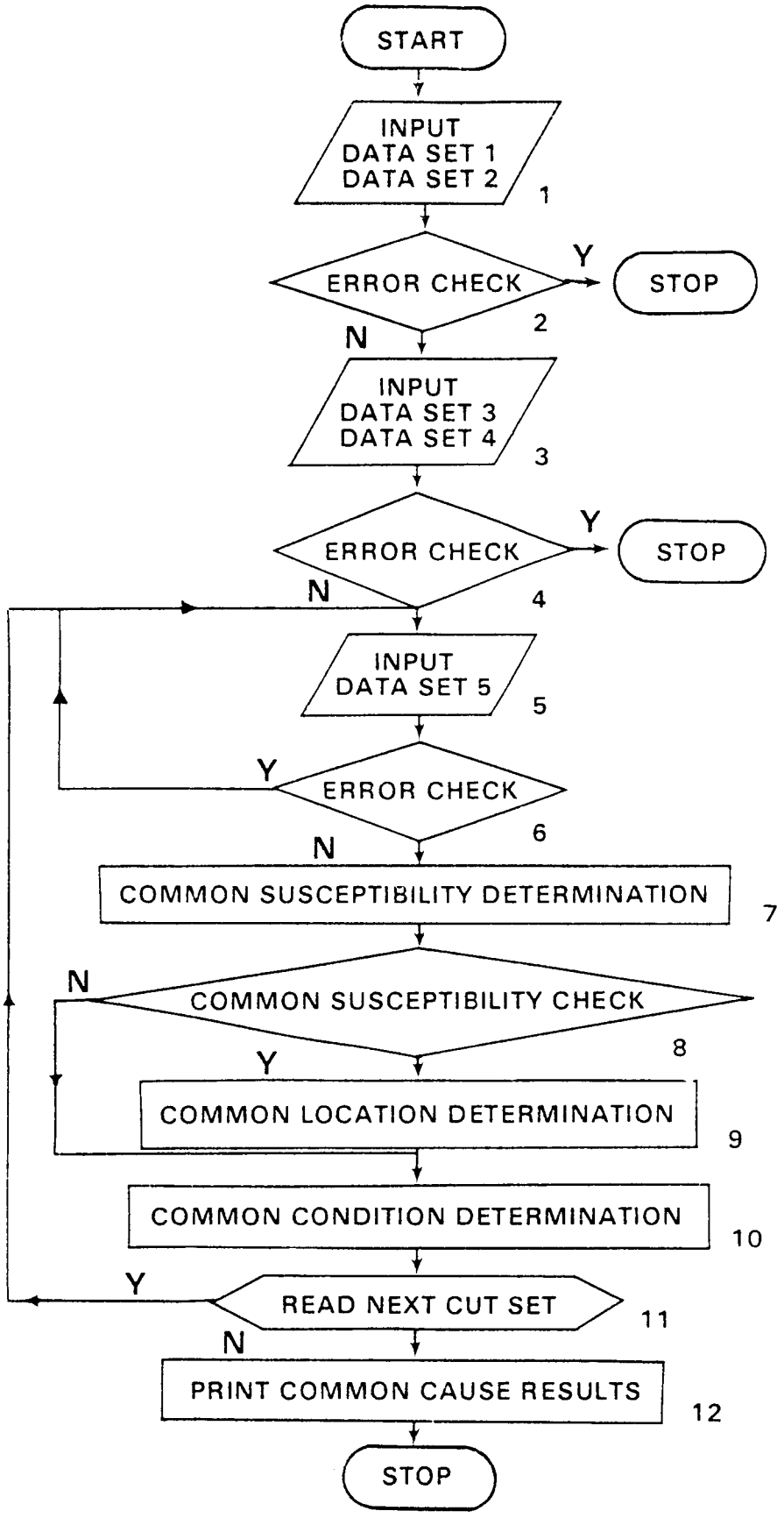


Figure I-1. BACFIRE Flow Chart.

[11]

## I-4. DESCRIPTION OF INPUT TO BACFIRE

Information necessary for BACFIRE-aided common cause failure analysis consists of five data sets:

1. Event Definition
2. Event Location References
3. Cause of Secondary Failure Library
4. Manufacturer Library
5. Hardware Minimal Cut Sets.

Each data set is preceded by a card with an asterisk (*) in column one and followed by a card with "END" in columns one through three. Information about the contents of each of the data sets can be supplied on a comment card starting in column three. These comments are used to identify the data set to the analyst and are not used in any way by the program. The proper order of the data sets is shown in Figure I-2. The input format will be discussed in order of submittal of the data sets.

BACFIRE examines column one on a data card that may be supplied before the asterisk card preceeding Data Set One. This card is optional. If "P" is punched in this column, the input for Data Sets One through Four will be printed as it is read by the program. This print option is useful for determining errors in the program input.

i. Data Set One: Event Definition

The first set of input for BACFIRE defines each event by providing the event description, its location, causes of secondary failure and a relative ranking of the failure characteristics. An event definition

must be supplied for each event that appears in the cut sets to be analyzed. Each event will require a minimum of two cards. The event data will be coded according to the form in Figure I-3. Table I-3 contains a description of the input for Data Set One.

Minimum sensitivity IMPCO. This data is supplied only once and on the one card immediately following the asterisk card. IMPCO is used to restrict the analysis. The sensitivity ranking must be greater than or equal to IMPCO for each event in the minimal cut set for a common cause candidate to be printed. A blank card must be supplied if no minimum sensitivity is supplied.

Event description C(I). Eight alphanumeric characters are used to identify a basic event. See Appendix I-A for details of an appropriate event naming scheme used during the Reactor Safety Study.[6] Any eight-character event description can be used, but it must be identical to the event descriptions used in the minimal cut sets.

Manufacturer MFG(I). A special data location is supplied for a particular special condition which deserves special consideration, usually manufacturer. This category will be checked based on the first criterion as are other special conditions. This variable is checked against Data Set Four to identify the particular common special condition.

Location LO(I,1). The first position in this array stores the number of locations used in defining the event.

Cause of secondary failure GCS(I,J,K). This array contains the qualitative failure characteristic assigned to each event in its respective category. There are three blocks for up to five one-character codes in each of three cause of secondary failure susceptibility categories. The

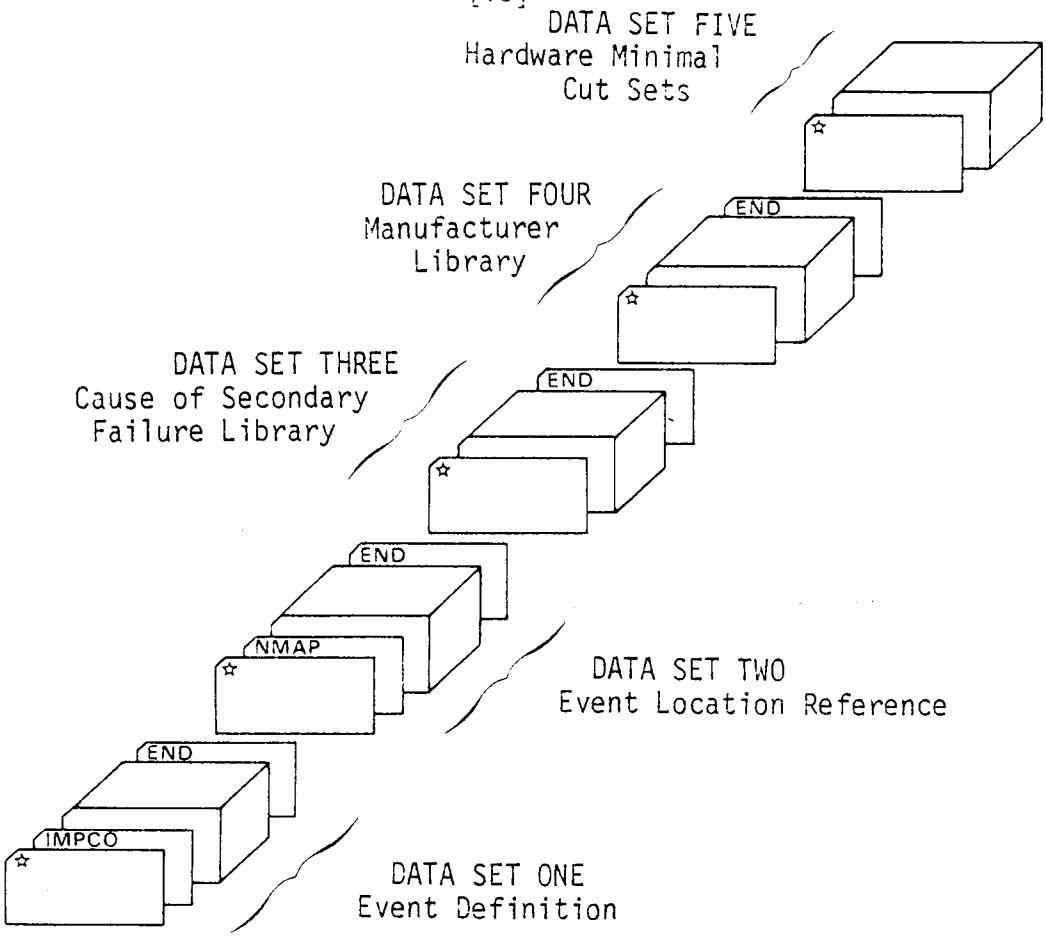


Figure I-2. BACFIRE Input Data Sets.

**COMMON CAUSE ANALYSIS**

| EVENT DESCRIPTION | | LAMBDA | TAU | | ERROR FACTOR (LAMBDA) | | ERROR FACTOR (TAU) | MFR | LOCATION | | | GENERIC CAUSE SUSCEPTIBILITY | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | CATEGORY 1 | CATEGORY 2 | CATEGORY 3 | CATEGORY 4 |
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| | | | | | | | | | | | | | | | | | |
| 00000000 12345678 | 01 90 | 11111111112 12345678 90 | 22222222223 12345678 90 | 31 | 33333 23456 | 37 | 33444 89012 | 43 | 44 | 44445 56789 | 51 | 5555 5234 | 55 | 55556 67890 | 66666 12345 | 66667 67890 | 77777777778 12345678 90 |

Figure I-3. BACFIRE Coding Form.

TABLE I-3

DESCRIPTION OF INPUT FOR DATA SET ONE

| Fortran Variable | Format | Column | Adjustment |
|---|---|---|---|
| One card per run | | | |
| IMPCO | I5 | 1-5 | Right |
| One set of following cards for each basic event | | | |
| Card 1. One card for each event definition | | | |
| C(I) | A8 | 1-8 | Left |
| MFG(I) | A1 | 44 | |
| LO(I,1) | I4 | 47-50 | Right |
| GCS(I,J,K) | | | |
| Category 1 | 5A1 | 56-60 | |
| Category 2 | 5A1 | 61-65 | |
| Category 3 | 5A1 | 66-70 | |
| Category 4 | 5A2 | 71-80 | Left |
| Card 2. One card for each event definition | | | |
| LO(I,2) | A4 | 47-50 | Left |
| IMP(I,J,K) | | | |
| Category 1 | 5I1 | 56-60 | |
| Category 2 | 5I1 | 61-65 | |
| Category 3 | 5I1 | 66-70 | |
| Category 4 | 5I2 | 71-80 | Right |
| Card 3. One card for each additional event location | | | |
| LO(I,J) | A4 | 47-50 | Left |

last block is for up to five two-character codes from the fourth category for special conditions. The related sensitivity ranking of each failure characteristic is supplied in the same column as the susceptibility or condition on the data card immediately following it.

Location LO(I,2). This position in the LO array stores the first location identified with the basic event.

Sensitivity ranking IMP(I,J,K). The sensitivity ranking assigned to each failure characteristic is stored in this array and is input in the same column as the susceptibility or special condition on the card immediately following the event description card (and on the first location card).

Location LO(I,J). These positions record any additional locations associated with a basic event. The cards are only supplied when more than one location has been identified for the basic event. (See example problem in Appendixes I-B and I-C.)

ii. Data Set Two: Event Location References

This data block cross references the location of the event definition to the proper domain on the various cause of secondary failure maps. Table I-4 contains the input description for Data Set Two.

Number of maps NMAP. This data is supplied only once and on the first card following the asterisk card. This is the number of different cause of secondary failure maps which are used in the system analysis. If this is zero, the card can be left blank and no other cards before the "END" card need to be supplied. This places all events in the same domain for each susceptibility for analysis by the second criterion.

Location and domain LOC(I); MAP(I,J). Each event location identified in the event definition is identified again here. The

TABLE I-4

DESCRIPTION OF INPUT FOR DATA SET TWO

| Fortran Variable | Format | Column | Adjustment |
|---|---|---|---|
| One card per run | | | |
| NMAP | I5 | 1-5 | Right |
| One card for each location in Data Set One | | | |
| LOC(I) | A4 | 11-14 | Left |
| MAP(I,1) | A4,1X | 16-19,20 | Left |
| MAP(I,2) | A4,1X | 21-24,25 | Left |
| . | | | |
| . | | | |
| . | | | |

location code, as it appeared in the event definition is followed by the domain code for the domain it appears in on map one, map two, etc. to map NMAP. (See example problem in Appendix I-B.)

iii. Data Set Three: Cause of Secondary Failure Library

This library relates susceptibility and special condition descriptions with the codes, category and the domain map which is applicable to its barriers. The input description for Data Set Three is in Table I-5.

Qualitative failure characteristic SUS(I,J). A 24-character description of each susceptibility and special condition is located in this array. This information is used to identify the common susceptibility or common special condition in the program output.

Qualitative failure characteristic Code ASSUS(I). This is the susceptibility and special condition codes assigned the failure characteristic. These correspond to the susceptibilities and special conditions assigned the basic events in Data Set One.

Category CTG(I). This variable identifies the category of failure characteristic code. The same code can be used in as many different categories as necessary. It is necessary to specify the special condition code as being used in category four.

Map MP(I). This variable identifies the cause of secondary failure with the map used to represent its domains. For special conditions, no map is necessary and this field can be left blank.

iv. Data Set Four: Manufacturer Library

This library serves the same purpose for a significant special condition as Data Set Three. The numerous different possible

TABLE I-5

DESCRIPTION OF INPUT FOR DATA SET THREE

| Fortran Variable | Format | Column | Adjustment |
|---|---|---|---|
| One card per qualitative failure characteristic | | | |
| SUS(I,J) | 3A8 | 1-24 | Left |
| ASSUS(I) | A2 | 30-31 | Left |
| CTG(I) | I1 | 35 | |
| MP(I) | I2 | 39-40 | Right |

manufacturers can create a long listing of their own. For these reasons a separate data array and library were created for use in determining the common condition of manufacturer. However, since this is checked by the first criterion, any significant special condition can be checked here. Coding on the event definitions is in Manufacturer MFG(I). A sensitivity of 9 is assigned a common cause candidate found by Data Set Four. Description for the input to Data Set Four is given in Table I-6.

Manufacturer MANU(I,J). A 24-character description of the manufacturer is stored in this array. This information is used to identify the common special condition in the program output.

Manufacturer code AMAN(J). This is the manufacturer code assigned the potential common cause of failure of manufacturer. These codes correspond to the manufacturer code assigned in Data Set One.

v. Data Set Five: Hardware Minimal Cut Sets

This data set contains the cut sets determined by other qualitative analyses which will be searched for common qualitative failure characteristics. Table I-7 contains the Data Set Five input description.

Number of events NCSM. This is the number of basic events which appears in the cut sets.

Event description CSM(I). The eight-character descriptions of the basic events appearing in the cut set are stored in this array. Continue coding on the following card in column 11 if there are more than seven basic events in the minimal cut set.

TABLE I-6

DESCRIPTION FOR INPUT FOR DATA SET FOUR

| Fortran Variable | Format | Column | Adjustment |
|---|---|---|---|
| One card per manufacturer | | | |
| MANU(I,J) | 3A8 | 1-24 | Left |
| AMAN(I) | A1 | 30 | |

TABLE I-7

DESCRIPTION FOR INPUT FOR DATA SET FIVE

| Fortran Variable | Format | Column | Adjustment |
|---|---|---|---|
| Minimum of one card per cut set | | | |
| NCSM | I5 | 1-5 | Right |
| CSM(1) | A8 | 11-18 | Left |
| CSM(2) | A8 | 21-28 | Left |
| . | | | |
| . | | | |
| . | | | |

## I-5. OUTPUT DESCRIPTION

The output from BACFIRE contains:

1. the common cause candidates, their failure commonalities and severity information
2. the potential causes of failure identified by BACFIRE.

This list of common cause candidates contains those cut sets that are found to have commonalities that are ranked higher than IMPCO. The minimum, maximum, average and sum of the sensitivity of the commonality are also listed for analyst reference.

A list of all qualitative failure characteristics input in Data Set Three and Data Set Four is printed. Following each potential cause of failure are the events identified by BACFIRE. These events represent the common cause candidates identified by the qualitative failure characteristic. The new cut set generated for common cause candidates identified by the first criterion consists of one event. Table I-8 contains the decoding information for the eight-character event.

The new cut set generated for common cause candidates identified by the second criterion also consist of one event. Table I-9 contains the decoding information for the events.

Optional output from BACFIRE consists of a complete listing of the data supplied in Data Sets One through Four (see Section I-4). These listings will not be needed once the analyst has the input information properly coded.

TABLE I-8

DECODING FOR FIRST CRITERION CUT SETS

| Position | Significance |
|---|---|
| 1,2 | The failure characteristic code (Table I-1) |
| 3 | The category of the failure characteristic<br>4 - special condition<br>5 - manufacturer |
| 4,5 | The common cause candidate number |
| 6-8 | The minimal cut set number |

TABLE I-9

DECODING FOR SECOND CRITERION CUT SETS

| Position | Significance |
|---|---|
| 1 | The cause of secondary failure code (Table I-2) |
| 2 | The category of the cause of secondary failure (1, 2, or 3) |
| 3 | The minimum sensitivity ranking in the common cause candidate |
| 4,5 | The common cause candidate number |
| 6-8 | The minimal cut set number |

[23]

REFERENCES


1. W. E. Vesely, and R. E. Narum. PREP and KITT: Computer Codes for the Automatic Evaluation of a Fault Tree, Idaho Nuclear, IN-1349, August, 1970.

2. R. B. Worrell. Set Equation Transformation Systems (SETS), Sandia Laboratories, SLA-73-0028A, July, 1973.

3. J. B. Fussell, E. B. Henry, and N. H. Marshall. MOCUS—A Computer Program to Obtain Minimal Sets from Fault Trees, Aerojet Nuclear Company, ANCR-1156, August, 1974.

4. G. R. Burdick, N. H. Marshall, and J. R. Wilson. COMCAN—A Computer Program for Common Cause Analysis, Aerojet Nuclear Company, ANCR-1156, August, 1974.

5. J. B. Fussell, G. R. Burdick, D. M. Rasmuson, J. R. Wilson, and J. C. Zipperer. A Collection of Methods for Reliability and Safety Engineering, Aerojet Nuclear Company, ANCR-1273, April, 1973.

6. Nuclear Regulatory Commission. REACTOR Safety Study—An Assessment of Accident Risks in U. S. Commercial Nuclear Power Plants. WASH-1400 (NUREG 75/014). Washington: Government Printing Office, October, 1975.

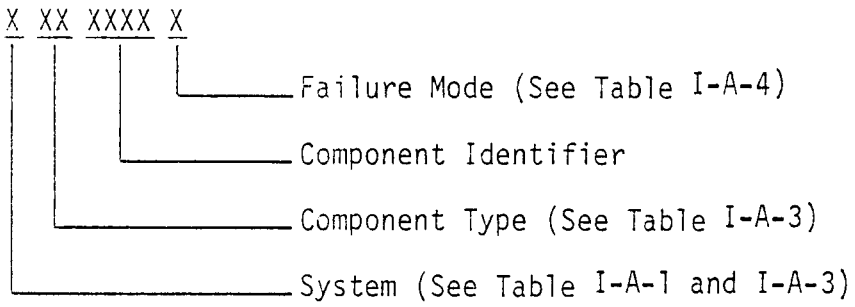
# APPENDIXES FOR APPENDIX I

# APPENDIX I-A

## BASIC EVENT CODING INFORMATION

### Event Naming[6]

Each unique basic input event shown on the logic model is given a unique eight-character code name in order to facilitate proper evaluation of the logic model. For example, a component failure event may appear several places on a logic model and on more than one logic model, but if it is the same component with the same failure mode it will have the same name. The coding scheme identifies events by system, component type, component identification, and failure mode as shown below.[1]




[1] The coding scheme described and used herein is a compromise of two coding schemes used in the construction of the PWR and BWR systems fault trees, respectively. It was desirable in the analysis of the systems to use where possible the component naming scheme used by the utility. These schemes differed in the two plants. The two naming schemes were modified somewhat to make them compatible where used in this report.

TABLE I-A-1

BWR SYSTEM IDENTIFICATION CODE[6]

| Code | System Name |
|---|---|
| 1 | Main Steam |
| 2 | Reactor Recirculation and Automatic Depressurization (ADS) |
| 3 | Reactor Protective System (RPS) |
| 4 | Feedwater |
| 8 | Offgas System |
| 9 | Vapor Suppression System (VSS) |
| A | Core Spray Injection System (CSIS) |
| B | Low Pressure Coolant Injection System (LPCIS) |
| C | Nuclear Boiler Vessel Instrumentation |
| D | High Pressure Service Water System (HPSWS) |
| E | Service Water |
| F | High Pressure Coolant Injection System (HPCIS) |
| L | Reactor Core Isolation Cooling System (RCICS) |
| M | Emergency Service Water System (ESWS) |
| N | Radwaste |
| Q | Electrical Power |
| R | Hydraulic Control Unit |
| S | Containment Leakage (CL) |
| U | Chilled Water |
| V | Standby Gas Treatment System (SBGTS) |
| X | Diesel Generator |
| Y | Containment Atmosphere Dilution System |
| Z | Reactor Building Heating and Ventilation |
| # | Fuel Pool |

TABLE I-A-2

PWR SYSTEM IDENTIFICATION CODE[6]

| Code | System Name |
|---|---|
| A | Accumulator (ACC) |
| G | Containment Leakage (CL) |
| N | Consequence Limiting Control System (CLCS) |
| K | Containment Heat Removal System (CHRS) |
| C | Containment Spray Injection System (CSIS) |
| D | Containment Spray Recirculation System (CSRS) |
| J | Electrical Power (EPS) |
| F | High Pressure Injection System (HPCIS) |
| H | High Pressure Recirculation System (HPCRS) |
| B | Low Pressure Injection System (LPIS) |
| E | Low Pressure Recirculation System (LPRS) |
| L | Sodium Hydroxide Addition System (SHAS) |
| I | Reactor Protection System (RPS) |
| M | Safety Injection Control System (SICS) |
| P | Auxiliary Feedwater (AF) |

TABLE I-A-3

COMPONENT CODE [6]

| | | | |
|---|---|---|---|
| | Mechanical Components | | |
| Accumulator | AC | Sluice Gate | SL |
| Blower | BL | Sump | SP |
| Control Rod Drive Unit | CD | Subtree | ST |
| Cover Plate | FA | Tank | TK |
| Damper | DM | Tubing | TG |
| Diesel | DL | Turbine | TB |
| Expansion Joint | XJ | Valve, Check | CV |
| Filter or Strainer | FL | Valve, Explosive Operated | EV |
| Gas Bottle | GB | Valve, Hydraulic Operated | HV |
| Gasket | GK | Valve, Manual | XV |
| Heat Exchanger | HE | Valve, Motor Operated | MV |
| Nozzle | NZ | Valve, Pneumatic Operated | AV |
| Orifice | OR | Valve, Relief | RV |
| Pipe | PP | Valve, Safety | SV |
| Pipe Cap | CP | Valve, Solenoid Operated | KV |
| Pressure Vessel | PV | Valve, Stop Check | DV |
| Pump | PM | Valve, Vacuum Relief | VV |
| Reactor Control Rod | ED | Vent | VT |
| Refrigeration Unit | RF | Well | WL |
| | Electrical Components | | |
| Amplifier | AM | Ground Switch | GS |
| Annunciator | AN | Relay | RE |
| Battery | BY | Relay or Switch Contact | CN |
| Battery Charger | BC | Reset Switch | RS |
| Bus | BS | Resistor, Temp. Device | RT |
| Cable | CA | Signal Comparator | AD |
| Circuit Breaker | CB | Switch, Pressure | PS |
| Clutch | CL | Switch, Torque | QS |

TABLE I-A-3 (continued)

| | | | |
|---|---|---|---|
| Control Switch | CS | Switch, Temperature | TS |
| Coil | CO | Terminal Board | TM |
| Detector | DI | Diode or Rectifier | DE |
| DC Power Supply | DC | Fuse | FU |
| Flow Switch | FS | Generator | GE |
| Heating Element | HG | Heat Tracing | HT |
| Input Module | IM | Test Pushbutton | SB |
| Inverter (solid state) | IV | Thermal Overload | OL |
| Level Switch | ES | Timer | TI |
| Light | LT | Transformer, Current | CT |
| Limit Switch | LS | Transformer, Potential (or control) | MP |
| Manual Switch | SW | Transformer, Power | TR |
| Motor | MO | Transmitter, Flow | TF |
| Motor Starter | MS | Transmitter, Level | TL |
| Neutron Detector | ND | Transmitter, Pressure | TP |
| Potentiometer | PT | Transmitter, Temperature | TT |
| Recorder | RC | Wire | WR |
| Lightning Arrester | LA | Event (where no component involved) | OO |

TABLE I-A-4

FAILURE MODE CODE[6]

| Failure Mode | |
|---|---|
| Closed | C |
| Disengaged | G |
| Does Not Close | K |
| Does Not Open | D |
| Does Not Start | A |
| Engaged | E |
| Exceeds Limit | M |
| Leakage | L |
| Loss of Function | F |
| Maintenance Fault | Y |
| No Input | N |
| Open | O |
| Open Circuit | B |
| Operational Fault | X |
| Overload | H |
| Plugged | P |
| Rupture | R |
| Short Circuit | Q |
| Short to Ground | S |
| Fault Transfer | T |

[33]

# APPENDIX I-B

## EXAMPLE PROBLEM

This example problem for BACFIRE analysis was developed by D. P. Wagner. Figure I-B-1 is the system logic model for a top event. Table I-B-1 contains the hardware minimal cut sets of the logic model. The minimal cut sets were determined by MOCUS.[3] The components along with their generic cause susceptibilities are listed in Table I-B-2. Also contained in this table are the physical locations assigned the components which correspond to the floor plan of Figure I-B-2. Some components are identified in more than one location. This illustrates components such as wiring or piping which may pass through various barriers to their susceptibilities. Figure I-B-3 is the three susceptibility maps used in the analysis. The I, S Map is used for impact and stress, the T Map for temperature and the V Map for vibration. The areas on these maps are the various domains for these causes of secondary failure. The areas of the floor plan of Figure I-B-2 are shown in the proper domains on each map. The domain data is tabulated in Table I-B-3.

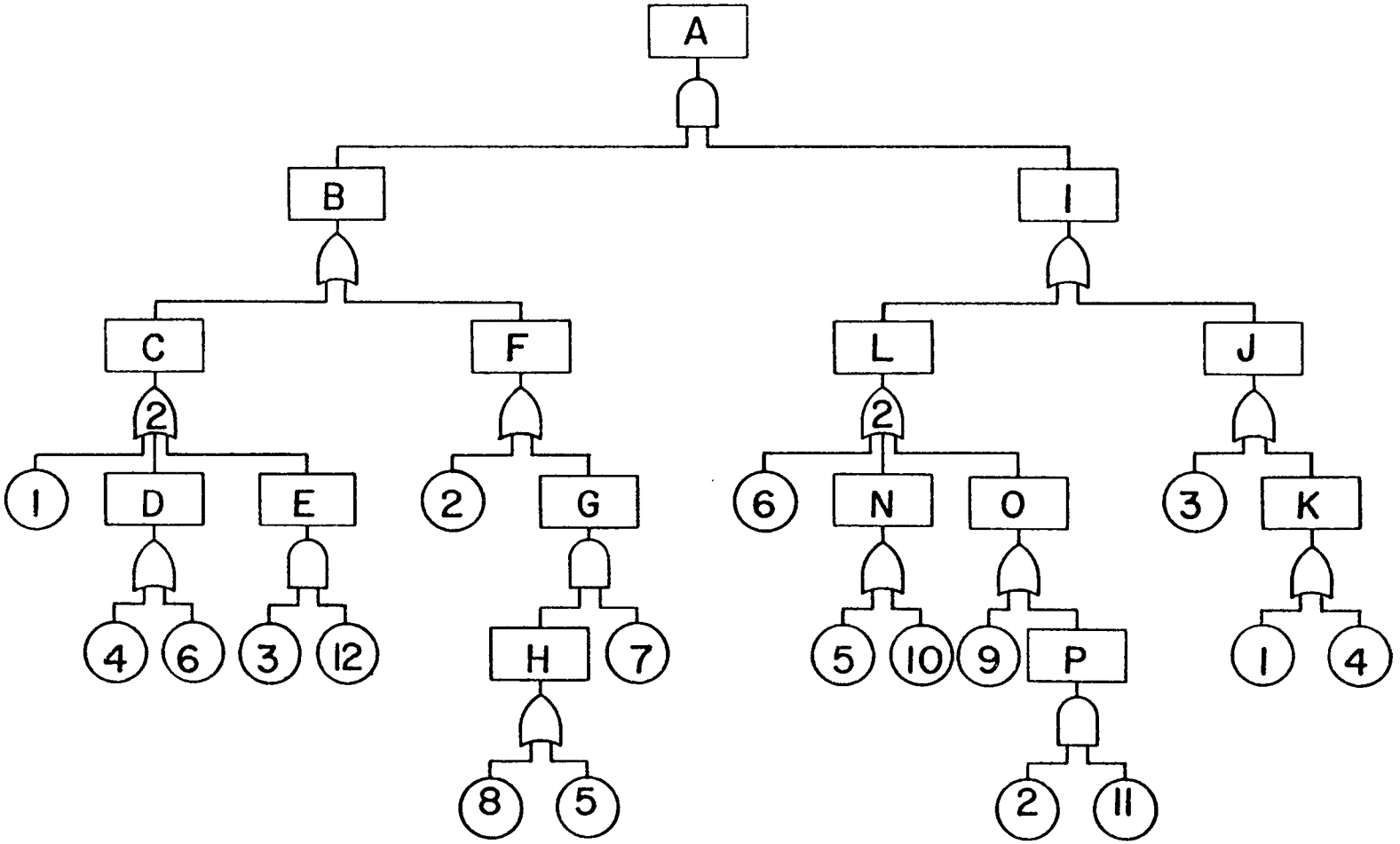



Figure I-B-1. Example Problem Fault Tree.

TABLE I-B-1

MINIMAL CUT SETS FOR EXAMPLE PROBLEM

| | | |
|---|---|---|
| 2, 1 | 5, 1, 7 | 1, 3, 12 |
| 2, 3 | 8, 1, 7 | 6, 3, 12 |
| 2, 4 | 5, 3, 7 | 2, 6, 5 |
| 4, 1 | 5, 4, 7 | 2, 6, 9 |
| 6, 1 | 4, 3, 12 | 2, 6, 10 |
| | 5, 2, 11 | 7, 6, 5 |
| 8, 7, 6, 9 | 8, 3, 7 | 7, 9, 5 |
| 8, 7, 6, 10 | 8, 4, 7 | 2, 9, 5 |
| 8, 7, 9, 10 | 6, 2, 11 | 2, 10, 9 |
| | 10, 2, 11 | |

TABLE I-B-2

COMMON CAUSE FAILURE DATA FOR THE EXAMPLE PROBLEM

| Basic Event | Physical Location | Qualitative Failure Characteristics: Generic Cause Susceptibilities (Category 1) | Qualitative Failure Characteristics: Special Conditions (Category 4) |
|---|---|---|---|
| 1 | 101<br>103<br>105<br>199 | I, S | E2, O1, I1 |
| 2 | 105 | I, S | E2, O1, I1 |
| 3 | 104 | I, T | O1, I3 |
| 4 | 104 | S, T | T2, I3 |
| 5 | 102 | T, V | O2, I3 |
| 6 | 102<br>104<br>106 | I, V | O1, I2 |
| 7 | 105 | I, V, S | O2, I2 |
| 8 | 105 | I, V, T | T2, I3 |
| 9 | 199 | S | E1, I3 |
| 10 | 106 | I, V, S, T | O2, I2 |
| 11 | 103<br>106<br>199 | S, T | T2, I3 |
| 12 | 104 | T | O1, I1 |

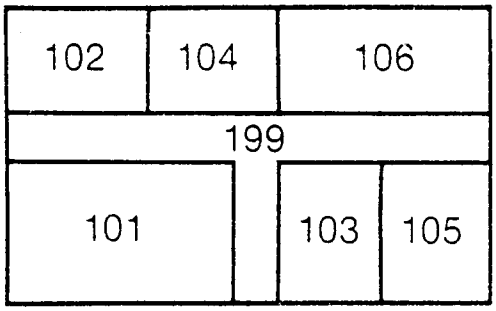



Figure I-B-2. Example Problem Floor Plan.

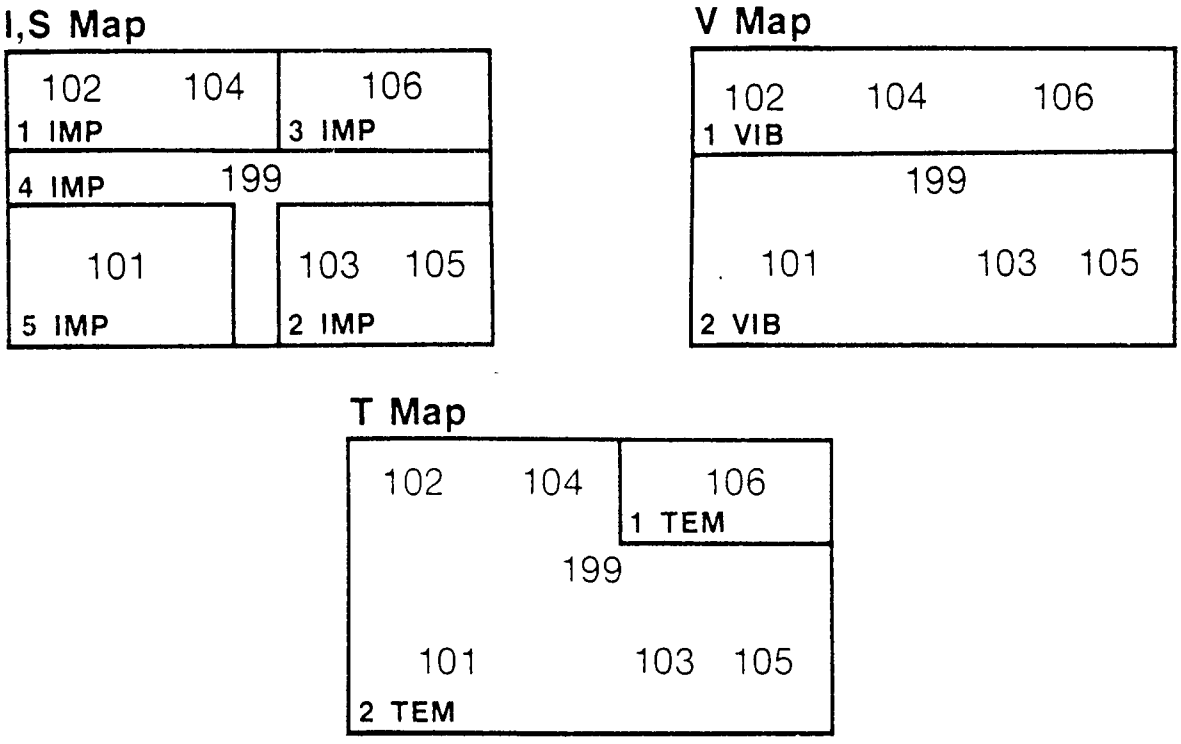



Figure I-B-3. Example Problem Susceptibility Maps.
I, S Map, Impact and Stress
V Map, Vibration
T Map, Temperature

TABLE I-B-3

GENERIC CAUSE SUSCEPTIBILITY DOMAINS FOR THE EXAMPLE PROBLEM

| Generic Cause | Domain | Physical Location |
|---|---|---|
| I, S | 1 IMP | 102, 104 |
| | 2 IMP | 103, 105 |
| | 3 IMP | 106 |
| | 4 IMP | 199 |
| | 5 IMP | 101 |
| T | 1 TEM | 106 |
| | 2 TEM | 101, 102, 103, 104, 105, 199 |
| V | 1 VIB | 102, 104, 106 |
| | 2 VIB | 101, 103, 105, 199 |

[39]

# APPENDIX I-C

## EXAMPLE PROBLEM INPUT

This appendix shows the coded input for BACFIRE aided analysis of the example problem in Appendix I-B. The figures contain the five data sets as described in Section I-4.

```
         10        20        30        40        50        60        70        80
----+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
*     DATA SET ONE

1                                                 4     IS              E2O1I1
1                                               101     46               8 6 2
1                                               103
1                                               105
1                                               199
2                                                       IS              E2O1I1
2                                               105     46               6 6 2
3                                                       IT              O1I3

         10        20        30        40        50        60        70        80
----+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
3                                               104     29               3 1 2
4                                                       ST              T2I3
4                                               104     85               6 9
5                                                       TV              O2I3
5                                               102     73               1 9
6                                                 3     IV              I2
6                                               102     33               9
6                                               104
6                                               106
7                                                       IVS             O2I2

         10        20        30        40        50        60        70        80
----+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
7                                               105     434              4 8
8                                                       IVT             T2I3
8                                               105     536              1 9
9                                                       S               E1I3
9                                               199     3                3 9
10                                                      IVST            O2I2
10                                              106     7842             4 8
11                                                3     ST              T2I3
11                                              103     85               6 9
11                                              106

         10        20        30        40        50        60        70        80
----+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
11                                              199
12                                                      T               O1I1
12                                              104     1                6 2
END
```

Figure I-C-1. Data Set One.

```
         10        20        30        40        50        60        70        80
---+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
*      DATA SET TWO
    3
          101  5IMP 2TEM 2VIB
          102  1IMP 2TEM 1VIB
          103  2IMP 2TEM 2VIB

         10        20        30        40        50        60        70        80
---+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
          104  1IMP 2TEM 1VIB
          105  2IMP 2TEM 2VIB
          106  3IMP 1TEM 1VIB
          199  4IMP 2TEM 2VIB
END

         10        20        30        40        50        60        70        80
---+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
```

Figure I-C-2. Data Set Two.

```
         10        20        30        40        50        60        70        80
---+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
*      DATA SET THREE
IMPACT                          I     1     1
STRESS                          S     1     1
TEMPERATURE                     T     1     2
VIBRATION                       V     1     3

         10        20        30        40        50        60        70        80
---+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
INSTALLATION CONTRCTR 1         I1    4
INSTALLATION CONTRCTR2          I2    4
INSTALLATION CONTRCTR 3         I3    4
TEST PROCEDURE 1                T1    4
TEST PROCEDURE 2                T2    4

         10        20        30        40        50        60        70        80
---+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
OPERATOR 1                      O1    4
OPERATOR 2                      O2    4
ENERGY SOURCE 1                 E1    4
ENERGY SOURCE 2                 E2    4
END

         10        20        30        40        50        60        70        80
---+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
        SAMPLE PROBLEM FOR DACFIRE USERS MANUAL -- DATA SET FOUR
*      DATA SET FOUR
END
```

Figure I-C-3. Data Sets Three and Four.

```
         10        20        30        40        50        60        70        80
----+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
*      DATA SET FIVE
     2    2         1
     2    2         3
     2    2         4
     2    4         1

         10        20        30        40        50        60        70        80
----+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
     2    6         1
     3    5         1         7
     3    8         1         7
     3    5         3         7
     3    5         4         7

         10        20        30        40        50        60        70        80
----+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
     3    4         3         12
     3    5         2         11
     3    8         3         7
     3    8         4         7
     3    6         2         11

         10        20        30        40        50        60        70        80
----+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
     3   10         2         11
     3    1         3         12
     3    6         3         12
     3    2         6         5
     3    2         6         9

         10        20        30        40        50        60        70        80
----+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
     3    2         6         10
     3    7         6         5
     3    7         9         5
     3    2         9         5
     3    2         10        9

         10        20        30        40        50        60        70        80
----+----|----+----|----+----|----+----|----+----|----+----|----+----|----+----|
     4    8         7         6         9
     4    8         7         6         10
     4    8         10        7         9
```

Figure I-C-4. Data Set Five.

# APPENDIX I-D

# EXAMPLE PROBLEM RESULTS

```
                                                                                    PAGE   1
                                                                                  BACFIRE VERSION 3  JULY/76

                    * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                    *                                                                   *
                    *      BACFIRE --- A PROGRAM TO OBTAIN COMMON CAUSE CANDIDATES      *
                    *                                                                   *
                    * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


NUMBER OF EVENTS WITH THEIR LOCATIONS AND GCS'S - - - -  12

NUMBER OF MAPS USED - - - - - - - - - - - - - - - - - -   3

NUMBER OF LOCATIONS AND THEIR MAP LOCATIONS - - - - - -   7

NUMBER OF GCS'S - - - - - - - - - - - - - - - - - - - -  13

NUMBER OF MANUFACTURERS - - - - - - - - - - - - - - - -   0

SENSITIVITY CUT OFF - - - - - - - - - - - - - - - - - -   6

                                                                                    PAGE   2
                                                                                  BACFIRE VERSION 3  JULY/76

*****************************************************************************************************************

                                          COMMON CAUSE CANDIDATES

*****************************************************************************************************************

      1)    2          1

        COMMON CONDITION -- FIRST CRITERION              RANK:  MIN       MAX       AVG       SUM

        ENERGY SOURCE 2                                          6         6         6        16
        OPERATOR 1                                               6         6         6        12
        INSTALLATION CONTRCTR 1                                  2         2         2         4

        COMMON SUSCEPTIBILITY -- SECOND CRITERION        RANK:  MIN       MAX       AVG       SUM

        IMPACT                                                   4         4         4         8
        STRESS                                                   6         6         6        12
```

2) 2 3

| COMMON CONDITION -- FIRST CRITERION | RANK: | MIN | MAX | AVG | SUM |
|---|---|---|---|---|---|
| OPERATOR 1 | | 3 | 6 | 4 | 9 |

3) 8 1 7

| COMMON SUSCEPTIBILITY -- SECOND CRITERION | RANK: | MIN | MAX | AVG | SUM |
|---|---|---|---|---|---|
| IMPACT | | 4 | 5 | 4 | 13 |

4) 4 3 12

| COMMON SUSCEPTIBILITY -- SECOND CRITERION | RANK: | MIN | MAX | AVG | SUM |
|---|---|---|---|---|---|
| TEMPERATURE | | 1 | 7 | 5 | 15 |

[45]

5) 1 3 12

| COMMON CONDITION -- FIRST CRITERION | RANK: | MIN | MAX | AVG | SUM |
|---|---|---|---|---|---|
| OPERATOR 1 | | 3 | 6 | 5 | 15 |

THE NUMBER OF CUT SETS TESTED IS 27

QUALITATIVE FAILURE CHARACTERISTICS

IMPACT
DOMAIN ZIMP
I14 1 1
I14 3 7

STRESS
DOMAIN ZIMP
S16 1 1

TEMPERATURE
DOMAIN ZTEM
T11 4 10

VIBRATION

INSTALLATION CONTROL 1
I14 1 1

INSTALLATION CONTROL 2

INSTALLATION CONTROL 3

TEST PROCEDURE 1

TEST PROCEDURE 2

OPERATOR 1
O14 1 1
O14 2 2
O14 5 15

OPERATOR 2

ENERGY SOURCE 1

---

ENERGY SOURCE 2
E24 1 1

END

THIS CONCLUDES THE OUTPUT FROM ASCRIBE.

# APPENDIX II

## COMMON CAUSE CANDIDATES OF THE CLINCH RIVER BREEDER REACTOR PLANT PROTECTIVE SYSTEMS DETERMINED BY BACFIRE

The basic events of the common cause candidates are the "dummy" events defined by D. P. Wagner[27] to represent the qualitative failure characteristics of branches of the logic model. The domains which are identified are also defined by Wagner.

```
                                                                                    PAGE   1
                                                                                    BACFIRE VERSION 3  JULY/76

                    * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                    *                                                                     *
                    *     BACFIRE --- A PROGRAM TO OBTAIN COMMON CAUSE CANDIDATES         *
                    *                                                                     *
                    * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *


NUMBER OF EVENTS WITH THEIR LOCATIONS AND GCS'S - - - -  17

NUMBER OF MAPS USED - - - - - - - - - - - - - - - - - -   9

NUMBER OF LOCATIONS AND THEIR MAP LOCATIONS - - - - - -  53

NUMBER OF GCS'S - - - - - - - - - - - - - - - - - - - -  18

NUMBER OF MANUFACTURERS - - - - - - - - - - - - - - - -   9

SENSITIVITY CUT OFF - - - - - - - - - - - - - - - - - -   0
```

## COMMON CAUSE CANDIDATES

1) PE001 SE012 PE002

| COMMON CONDITION -- FIRST CRITERION | RANK: | MIN | MAX | AVG | SUM |
|---|---|---|---|---|---|
| WESTON | | 0 | 0 | 0 | 0 |

| COMMON SUSCEPTIBILITY -- SECOND CRITERION | RANK: | MIN | MAX | AVG | SUM |
|---|---|---|---|---|---|
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |

2) PE001 SE012 PE003

| COMMON CONDITION -- FIRST CRITERION | RANK: | MIN | MAX | AVG | SUM |
|---|---|---|---|---|---|
| WESTON | | 0 | 0 | 0 | 0 |

| COMMON SUSCEPTIBILITY -- SECOND CRITERION | RANK: | MIN | MAX | AVG | SUM |
|---|---|---|---|---|---|
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |

31 PE002 SE012 PE003

| COMMON CONDITION -- FIRST CRITERION | RANK: | MIN | MAX | AVG | SUM |
|---|---|---|---|---|---|
| WESTON | | 0 | 0 | 0 | 0 |

| COMMON SUSCEPTIBILITY -- SECOND CRITERION | RANK: | MIN | MAX | AVG | SUM |
|---|---|---|---|---|---|
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |

4)  PE001  SE013  PE002

| COMMON SUSCEPTIBILITY -- SECOND CRITERION | RANK | MIN | MAX | AVG | SUM |
|---|---|---|---|---|---|
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |

5) PE001 SE023 PE002

| COMMON SUSCEPTIBILITY -- SECOND CRITERION | RANK: | MIN | MAX | AVG | SUM |
|---|---|---|---|---|---|
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |

*) PE001 SE013 PE003

| COMMON SUSCEPTIBILITY -- SECOND CRITERION | RANK: | MIN | MAX | AVG | SUM |
|---|---|---|---|---|---|
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |

7) PE001 SE023 PE003

| COMMON SUSCEPTIBILITY -- SECOND CRITERION | RANK: | MIN | MAX | AVG | SUM |
|---|---|---|---|---|---|
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |

8) PE002 SE013 PE003

| COMMON SUSCEPTIBILITY -- SECOND CRITERION | RANK: | MIN | MAX | AVG | SUM |
|---|---|---|---|---|---|
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |

9) PE002 SE023 PE003

| COMMON SUSCEPTIBILITY -- SECOND CRITERION | RANK: | MIN | MAX | AVG | SUM |
|---|---|---|---|---|---|
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| IMPACT | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| TEMPERATURE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| ELECTROMAG. INTERFERENCE | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (ACID) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |
| CORROSION (OXIDATION) | | 0 | 0 | 0 | 0 |

THE NUMBER OF CUT SETS TESTED IS 196

QUALITATIVE FAILURE CHARACTERISTICS

IMPACT

| DOMAIN | | | | | |
|---|---|---|---|---|---|
| I013 | I | 1 | 0 | 1 | 5 |
| | I | 1 | 0 | 2 | 6 |
| | I | 1 | 0 | 3 | 7 |
| | I | 1 | 0 | 4 | 18 |
| | I | 1 | 0 | 5 | 19 |
| | I | 1 | 0 | 6 | 21 |
| | I | 1 | 0 | 7 | 22 |
| | I | 1 | 0 | 8 | 24 |
| | I | 1 | 0 | 9 | 25 |
| I001 | I | 1 | 0 | 1 | 5 |
| | I | 1 | 0 | 2 | 6 |
| | I | 1 | 0 | 3 | 7 |
| | I | 1 | 0 | 4 | 18 |
| | I | 1 | 0 | 5 | 19 |
| | I | 1 | 0 | 6 | 21 |
| | I | 1 | 0 | 7 | 22 |
| | I | 1 | 0 | 8 | 24 |
| | I | 1 | 0 | 9 | 25 |
| I002 | I | 1 | 0 | 1 | 5 |
| | I | 1 | 0 | 2 | 6 |
| | I | 1 | 0 | 3 | 7 |
| | I | 1 | 0 | 4 | 18 |
| | I | 1 | 0 | 5 | 19 |
| | I | 1 | 0 | 6 | 21 |
| | I | 1 | 0 | 7 | 22 |
| | I | 1 | 0 | 8 | 24 |
| | I | 1 | 0 | 9 | 25 |
| I003 | I | 1 | 0 | 1 | 5 |
| | I | 1 | 0 | 2 | 6 |
| | I | 1 | 0 | 3 | 7 |
| | I | 1 | 0 | 4 | 18 |
| | I | 1 | 0 | 5 | 19 |
| | I | 1 | 0 | 6 | 21 |
| | I | 1 | 0 | 7 | 22 |
| | I | 1 | 0 | 8 | 24 |
| | I | 1 | 0 | 9 | 25 |

VIBRATION

GRIT

STRESS

TEMPERATURE

| DOMAIN | | | | | |
|---|---|---|---|---|---|
| T011 | T | 1 | 0 | 1 | 5 |
| | T | 1 | 0 | 2 | 6 |
| | T | 1 | 0 | 3 | 7 |
| | T | 1 | 0 | 4 | 18 |
| | T | 1 | 0 | 5 | 19 |
| | T | 1 | 0 | 6 | 21 |
| | T | 1 | 0 | 7 | 22 |
| | T | 1 | 0 | 8 | 24 |
| | T | 1 | 0 | 9 | 25 |
| T001 | T | 1 | 0 | 1 | 5 |
| | T | 1 | 0 | 2 | 6 |
| | T | 1 | 0 | 3 | 7 |
| | T | 1 | 0 | 4 | 18 |
| | T | 1 | 0 | 5 | 19 |
| | T | 1 | 0 | 6 | 21 |
| | T | 1 | 0 | 7 | 22 |
| | T | 1 | 0 | 8 | 24 |
| | T | 1 | 0 | 9 | 25 |
| T002 | T | 1 | 0 | 1 | 5 |
| | T | 1 | 0 | 2 | 6 |
| | T | 1 | 0 | 3 | 7 |
| | T | 1 | 0 | 4 | 18 |
| | T | 1 | 0 | 5 | 19 |
| | T | 1 | 0 | 6 | 21 |
| | T | 1 | 0 | 7 | 22 |
| | T | 1 | 0 | 8 | 24 |
| | T | 1 | 0 | 9 | 25 |
| T003 | T | 1 | 0 | 1 | 5 |
| | T | 1 | 0 | 2 | 6 |
| | T | 1 | 0 | 3 | 7 |
| | T | 1 | 0 | 4 | 18 |
| | T | 1 | 0 | 5 | 19 |
| | T | 1 | 0 | 6 | 21 |
| | T | 1 | 0 | 7 | 22 |
| | T | 1 | 0 | 8 | 24 |
| | T | 1 | 0 | 9 | 25 |
| T004 | T | 1 | 0 | 1 | 5 |
| | T | 1 | 0 | 2 | 6 |
| | T | 1 | 0 | 3 | 7 |
| | T | 1 | 0 | 4 | 18 |
| | T | 1 | 0 | 5 | 19 |
| | T | 1 | 0 | 6 | 21 |
| | T | 1 | 0 | 7 | 22 |
| | T | 1 | 0 | 8 | 24 |
| | T | 1 | 0 | 9 | 25 |

PRESSURE

ELECTROMAG. INTERFERENCE

| DOMAIN | | | | | |
|---|---|---|---|---|---|
| E002 | E | 2 | 0 | 1 | 5 |
| | E | 2 | 0 | 2 | 6 |
| | E | 2 | 0 | 3 | 7 |
| | E | 2 | 0 | 4 | 18 |
| | E | 2 | 0 | 5 | 19 |
| | E | 2 | 0 | 6 | 21 |
| | E | 2 | 0 | 7 | 22 |
| | E | 2 | 0 | 8 | 24 |
| | E | 2 | 0 | 9 | 25 |
| E003 | E | 2 | 0 | 1 | 5 |
| | E | 2 | 0 | 2 | 6 |
| | E | 2 | 0 | 3 | 7 |
| | E | 2 | 0 | 4 | 18 |
| | E | 2 | 0 | 5 | 19 |
| | E | 2 | 0 | 6 | 21 |
| | E | 2 | 0 | 7 | 22 |
| | E | 2 | 0 | 8 | 24 |
| | E | 2 | 0 | 9 | 25 |
| E004 | E | 2 | 0 | 1 | 5 |
| | E | 2 | 0 | 2 | 6 |
| | E | 2 | 0 | 3 | 7 |
| | E | 2 | 0 | 4 | 18 |
| | E | 2 | 0 | 5 | 19 |
| | E | 2 | 0 | 6 | 21 |
| | E | 2 | 0 | 7 | 22 |
| | E | 2 | 0 | 8 | 24 |
| | E | 2 | 0 | 9 | 25 |

CONDUCTING MEDIUM

OUT OF TOLERANCE VOLTAGE

OUT OF TOLERANCE CURRENT

```
CORROSION (ACID)
  DOMAIN  A011
          A  3  0      1      5
          A  3  0      2      6
          A  3  0      3      7
          A  3  0      4     18
          A  3  0      5     19
          A  3  0      6     21
          A  3  0      7     22
          A  3  0      8     24
          A  3  0      9     25
  DOMAIN  A001
          A  3  0      1      5
          A  3  0      2      6
          A  3  0      3      7
          A  3  0      4     18
          A  3  0      5     19
          A  3  0      6     21
          A  3  0      7     22
          A  3  0      8     24
          A  3  0      9     25
  DOMAIN  A002
          A  3  0      1      5
          A  3  0      2      6
          A  3  0      3      7
          A  3  0      4     18
          A  3  0      5     19
          A  3  0      6     21
          A  3  0      7     22
          A  3  0      8     24
          A  3  0      9     25
  DOMAIN  A003
          A  3  0      1      5
          A  3  0      2      6
          A  3  0      3      7
          A  3  0      4     18
          A  3  0      5     19
          A  3  0      6     21
          A  3  0      7     22
          A  3  0      8     24
          A  3  0      9     25
  DOMAIN  A004
          A  3  0      1      5
          A  3  0      2      6
          A  3  0      3      7
          A  3  0      4     18
          A  3  0      5     19
          A  3  0      6     21
          A  3  0      7     22
          A  3  0      8     24
          A  3  0      9     25
```

```
CORROSION (OXIDATION)
  DOMAIN  A011
          0  3  0      1      5
          0  3  0      2      6
          0  3  0      3      7
          0  3  0      4     18
          0  3  0      5     19
          0  3  0      6     21
          0  3  0      7     22
          0  3  0      8     24
          0  3  0      9     25
  DOMAIN  A001
          0  3  0      1      5
          0  3  0      2      6
          0  3  0      3      7
          0  3  0      4     18
          0  3  0      5     19
          0  3  0      6     21
          0  3  0      7     22
          0  3  0      8     24
          0  3  0      9     25
  DOMAIN  A002
          0  3  0      1      5
          0  3  0      2      6
          0  3  0      3      7
          0  3  0      4     18
          0  3  0      5     19
          0  3  0      6     21
          0  3  0      7     22
          0  3  0      8     24
          0  3  0      9     25
  DOMAIN  A003
          0  3  0      1      5
          0  3  0      2      6
          0  3  0      3      7
          0  3  0      4     18
          0  3  0      5     19
          0  3  0      6     21
          0  3  0      7     22
          0  3  0      8     24
          0  3  0      9     25
  DOMAIN  A004
          0  3  0      1      5
          0  3  0      2      6
          0  3  0      3      7
          0  3  0      4     18
          0  3  0      5     19
          0  3  0      6     21
          0  3  0      7     22
          0  3  0      8     24
          0  3  0      9     25
```

GENERAL ATOMIC

STATHAM

WESTERN PIPE

GENERAL ELECTRIC

WESTON

| | | | |
|---|---|---|---|
| X1 | .4 | 1 | 5 |
| X1 | 4 | 2 | 6 |
| X1 | 4 | 3 | 7 |

BURNS & ROE

GENERAL ATOMIC

STATHAM

WESTERN PIPE

GENERAL ELECTRIC

WESTON

BURNS-ROE

ROYAL INDUSTRIES

WESTINGHOUSE

ELMIRA-WESTINGHOUSE

THIS CONCLUDES THE OUTPUT FROM BACFIRE.

# APPENDIX III

## THE TOP EVENT, LOSS OF CAPABILITY TO SHUT DOWN, RELIABILITY CHARACTERISTICS PREDICTED BY SUPERPOCUS

**********
* PROBLEM TITLE FOR THIS ANALYSIS BYPOCUS . .  CRBRP  PPS *
**********

NUMBER OF BASIC EVENTS AND INHIBIT CONDITIONS (NCOMP) = 20

BASIC EVENT DATA (LAMBDA AND TAU)
(NON-POSITIVE TAU DENOTES NON-REPAIR)
(NON-POSITIVE LAMDA DENOTES INHIBIT CONDITION)

| BASIC EVENT INDEX | LAMBDA | TAU |
|---|---|---|
| 1 | 1.000000000-10 | 0.0 |
| 2 | 1.000000000-10 | 0.0 |
| 3 | 1.000000000-10 | 0.0 |
| 4 | 1.000000000-10 | 0.0 |
| 5 | 1.000000000-10 | 0.0 |
| 6 | 1.000000000-10 | 0.0 |
| 7 | 1.000000000-10 | 0.0 |
| 8 | 1.000000000-10 | 0.0 |
| 9 | 1.000000000-10 | 0.0 |
| 10 | 1.000000000-11 | 0.0 |
| 11 | 1.000000000-11 | 0.0 |
| 12 | 1.000000000-11 | 0.0 |
| 13 | 5.000000000-11 | 0.0 |
| 14 | 5.000000000-10 | 0.0 |
| 15 | 5.000000000-10 | 0.0 |
| 16 | 5.000000000-10 | 0.0 |
| 17 | 1.000000000-10 | 0.0 |
| 18 | 4.300000000-06 | 1.000000000 00 |
| 19 | 1.000000000-09 | 0.0 |
| 20 | 1.000000000-10 | 0.0 |

NUMBER OF TIME POINTS (NTPT) = 4

TIME POINTS FOR DELTA NON-POSITIVE (TOT(J))-IN HOURS...
2.160000000 03  4.320000000 03  6.540000000 03  8.760000000 03

NUMBER OF SETS (MCUT) = 20

SET INFORMATION

| | | | |
|---|---|---|---|
| SET NUMBER 1. WITH BASIC EVENTS - 1 | | SET NUMBER 11. WITH BASIC EVENTS - 11 | |
| SET NUMBER 2. WITH BASIC EVENTS - 2 | | SET NUMBER 12. WITH BASIC EVENTS - 12 | |
| SET NUMBER 3. WITH BASIC EVENTS - 3 | | SET NUMBER 13. WITH BASIC EVENTS - 13 | |
| SET NUMBER 4. WITH BASIC EVENTS - 4 | | SET NUMBER 14. WITH BASIC EVENTS - 14 | |
| SET NUMBER 5. WITH BASIC EVENTS - 5 | | SET NUMBER 15. WITH BASIC EVENTS - 15 | |
| SET NUMBER 6. WITH BASIC EVENTS - 6 | | SET NUMBER 16. WITH BASIC EVENTS - 16 | |
| SET NUMBER 7. WITH BASIC EVENTS - 7 | | SET NUMBER 17. WITH BASIC EVENTS - 17 | |
| SET NUMBER 8. WITH BASIC EVENTS - 8 | | SET NUMBER 18. WITH BASIC EVENTS - 18 | |
| SET NUMBER 9. WITH BASIC EVENTS - 9 | | SET NUMBER 19. WITH BASIC EVENTS - 19 | |
| SET NUMBER 10. WITH BASIC EVENTS - 10 | | SET NUMBER 20. WITH BASIC EVENTS - 20 | |

**********
*****RELIABILITY ANALYSIS FOR THE CUT SETS*****
**********

CHARACTERISTICS FOR MODE 1

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 2.15999977D-07 | 0.9999997840000 | 2.16000000D-07 | 0.9999997840000 | 1.69428056D-02 |
| 4380.00 | 4.37999904D-07 | 0.9999995620001 | 4.38000000D-07 | 0.9999995620000 | 2.09385403D-02 |
| 6540.00 | 6.53999786D-07 | 0.9999993460002 | 6.54000000D-07 | 0.9999993460000 | 2.26555125D-02 |
| 8760.00 | 8.75999616D-07 | 0.9999991240004 | 8.76000000D-07 | 0.9999991240000 | 2.36522014D-02 |

CHARACTERISTICS FOR MODE 2

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 2.15999977D-07 | 0.9999997840000 | 2.16000000D-07 | 0.9999997840000 | 1.69428056D-02 |
| 4380.00 | 4.37999904D-07 | 0.9999995620001 | 4.38000000D-07 | 0.9999995620000 | 2.09385403D-02 |
| 6540.00 | 6.53999786D-07 | 0.9999993460002 | 6.54000000D-07 | 0.9999993460000 | 2.26555125D-02 |
| 8760.00 | 8.75999616D-07 | 0.9999991240004 | 8.76000000D-07 | 0.9999991240000 | 2.36522014D-02 |

CHARACTERISTICS FOR MODE 3

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 2.15999977D-07 | 0.9999997840000 | 2.16000000D-07 | 0.9999997840000 | 1.69428056D-02 |
| 4380.00 | 4.37999904D-07 | 0.9999995620001 | 4.38000000D-07 | 0.9999995620000 | 2.09385403D-02 |
| 6540.00 | 6.53999786D-07 | 0.9999993460002 | 6.54000000D-07 | 0.9999993460000 | 2.26555125D-02 |
| 8760.00 | 8.75999616D-07 | 0.9999991240004 | 8.76000000D-07 | 0.9999991240000 | 2.36522014D-02 |

CHARACTERISTICS FOR MODE 4

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 2.15999977D-07 | 0.9999997840000 | 2.16000000D-07 | 0.9999997840000 | 1.69428056D-02 |
| 4380.00 | 4.37999904D-07 | 0.9999995620001 | 4.38000000D-07 | 0.9999995620000 | 2.09385403D-02 |
| 6540.00 | 6.53999786D-07 | 0.9999993460002 | 6.54000000D-07 | 0.9999993460000 | 2.26555125D-02 |
| 8760.00 | 8.75999616D-07 | 0.9999991240004 | 8.76000000D-07 | 0.9999991240000 | 2.36522014D-02 |

CHARACTERISTICS FOR MODE 5

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 2.15999977D-07 | 0.9999997840000 | 2.16000000D-07 | 0.9999997840000 | 1.69428056D-02 |
| 4380.00 | 4.37999904D-07 | 0.9999995620001 | 4.38000000D-07 | 0.9999995620000 | 2.09385403D-02 |
| 6540.00 | 6.53999786D-07 | 0.9999993460002 | 6.54000000D-07 | 0.9999993460000 | 2.26555125D-02 |
| 8760.00 | 8.75999616D-07 | 0.9999991240004 | 8.76000000D-07 | 0.9999991240000 | 2.36522014D-02 |

CHARACTERISTICS FOR MODE 6

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 2.159999770-07 | 0.9999997840000 | 2.160000000-07 | 0.9999997840000 | 1.694280550-02 |
| 4380.00 | 4.379999040-07 | 0.9999995620001 | 4.380000000-07 | 0.9999995620000 | 2.093854030-02 |
| 6540.00 | 6.539997860-07 | 0.9999993460002 | 6.540000000-07 | 0.9999993460000 | 2.265551250-02 |
| 8760.00 | 8.759996160-07 | 0.9999991240004 | 8.760000000-07 | 0.9999991240000 | 2.365220140-02 |

CHARACTERISTICS FOR MODE 7

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 2.159999770-07 | 0.9999997840000 | 2.160000000-07 | 0.9999997840000 | 1.694280560-02 |
| 4380.00 | 4.379999040-07 | 0.9999995620001 | 4.380000000-07 | 0.9999995620000 | 2.093854030-02 |
| 6540.00 | 6.539997860-07 | 0.9999993460002 | 6.540000000-07 | 0.9999993460000 | 2.265551250-02 |
| 8760.00 | 8.759996160-07 | 0.9999991240004 | 8.760000000-07 | 0.9999991240000 | 2.365220140-02 |

CHARACTERISTICS FOR MODE 8

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 2.159999770-07 | 0.9999997840000 | 2.160000000-07 | 0.9999997840000 | 1.694280560-02 |
| 4380.00 | 4.379999040-07 | 0.9999995620001 | 4.380000000-07 | 0.9999995620000 | 2.093854030-02 |
| 6540.00 | 6.539997860-07 | 0.9999993460002 | 6.540000000-07 | 0.9999993460000 | 2.265551250-02 |
| 8760.00 | 8.759996160-07 | 0.9999991240004 | 8.760000000-07 | 0.9999991240000 | 2.365220140-02 |

CHARACTERISTICS FOR MODE 9

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 2.159999770-07 | 0.9999997840000 | 2.160000000-07 | 0.9999997840000 | 1.694280560-02 |
| 4380.00 | 4.379999040-07 | 0.9999995620001 | 4.380000000-07 | 0.9999995620000 | 2.093854030-02 |
| 6540.00 | 6.539997860-07 | 0.9999993460002 | 6.540000000-07 | 0.9999993460000 | 2.265551250-02 |
| 8760.00 | 8.759996160-07 | 0.9999991240004 | 8.760000000-07 | 0.9999991240000 | 2.365220140-02 |

CHARACTERISTICS FOR MODE 10

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 2.159999980-08 | 0.9999999784000 | 2.160000000-08 | 0.9999999784000 | 1.694280730-03 |
| 4380.00 | 4.379999900-08 | 0.9999999562000 | 4.380000000-08 | 0.9999999562000 | 2.093854440-03 |
| 6540.00 | 6.539999730-08 | 0.9999999346000 | 6.540000000-08 | 0.9999999346000 | 2.265551920-03 |
| 8760.00 | 8.759999620-08 | 0.9999999124000 | 8.760000000-08 | 0.9999999124000 | 2.365221070-03 |

CHARACTERISTICS FOR MODE 11

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 2.15999998D-08 | 0.9999999784000 | 2.16000000D-08 | 0.9999999784000 | 1.69428073D-03 |
| 4380.00 | 4.37999990D-08 | 0.9999999562000 | 4.38000000D-08 | 0.9999999562000 | 2.09365444D-03 |
| 6540.00 | 6.53999978D-08 | 0.9999999346000 | 6.54000000D-08 | 0.9999999346000 | 2.26555192D-03 |
| 8760.00 | 8.75999962D-08 | 0.9999999124000 | 8.76000000D-08 | 0.9999999124000 | 2.36522107D-03 |

CHARACTERISTICS FOR MODE 12

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 2.15999998D-08 | 0.9999999784000 | 2.16000000D-08 | 0.9999999784000 | 1.69428073D-03 |
| 4380.00 | 4.37999990D-08 | 0.9999999562000 | 4.38000000D-08 | 0.9999999562000 | 2.09365444D-03 |
| 6540.00 | 6.53999978D-08 | 0.9999999346000 | 6.54000000D-08 | 0.9999999346000 | 2.26555192D-03 |
| 8760.00 | 8.75999962D-08 | 0.9999999124000 | 8.76000000D-08 | 0.9999999124000 | 2.36522107D-03 |

CHARACTERISTICS FOR MODE 13

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 1.07999994D-07 | 0.9999998920000 | 1.08000000D-07 | 0.9999998920000 | 8.47140328D-03 |
| 4380.00 | 2.18999976D-07 | 0.9999997810000 | 2.19000000D-07 | 0.9999997810000 | 1.04692713D-02 |
| 6540.00 | 3.26999947D-07 | 0.9999996730001 | 3.27000000D-07 | 0.9999996730000 | 1.13277581D-02 |
| 8760.00 | 4.37999940D-07 | 0.9999995620001 | 4.38000000D-07 | 0.9999995620000 | 1.18261033D-02 |

CHARACTERISTICS FOR MODE 14

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 1.07999942D-06 | 0.9999989200006 | 1.08000000D-06 | 0.9999989200000 | 8.47139916D-02 |
| 4380.00 | 2.18999760D-06 | 0.9999978100024 | 2.19000000D-06 | 0.9999978100000 | 1.04692610D-01 |
| 6540.00 | 3.26999665D-06 | 0.9999967300053 | 3.27000000D-06 | 0.9999967300000 | 1.13277414D-01 |
| 8760.00 | 4.37999041D-06 | 0.9999956200096 | 4.38000000D-06 | 0.9999956200000 | 1.18260800D-01 |

CHARACTERISTICS FOR MODE 15

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 1.07999942D-06 | 0.9999989200006 | 1.08000000D-06 | 0.9999989200000 | 8.47139916D-02 |
| 4380.00 | 2.18999760D-06 | 0.9999978100024 | 2.19000000D-06 | 0.9999978100000 | 1.04692610D-01 |
| 6540.00 | 3.26999665D-06 | 0.9999967300053 | 3.27000000D-06 | 0.9999967300000 | 1.13277414D-01 |
| 8760.00 | 4.37999041D-06 | 0.9999956200096 | 4.38000000D-06 | 0.9999956200000 | 1.18260800D-01 |

CHARACTERISTICS FOR MODE 16

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 1.07999942D-06 | 0.99999892000006 | 1.08000000D-06 | 0.99999892000000 | 8.47139916D-02 |
| 4380.00 | 2.18999760D-06 | 0.99999781000024 | 2.19000000D-06 | 0.99999781000000 | 1.04692610D-01 |
| 6540.00 | 3.26999465D-06 | 0.99999673000053 | 3.27000000D-06 | 0.99999673000000 | 1.13277414D-01 |
| 8760.00 | 4.37999041D-06 | 0.99999562000096 | 4.38000000D-06 | 0.99999562000000 | 1.18260800D-01 |

CHARACTERISTICS FOR MODE 17

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 2.15999770D-07 | 0.99999978400000 | 2.16000000D-07 | 0.99999978400000 | 1.69428056D-02 |
| 4380.00 | 4.37999040D-07 | 0.99999956200001 | 4.38000000D-07 | 0.99999956200000 | 2.09385403D-02 |
| 6540.00 | 6.53999860D-07 | 0.99999934600002 | 6.54000000D-07 | 0.99999934600000 | 2.26555125D-02 |
| 8760.00 | 8.75999616D-07 | 0.99999912400004 | 8.76000000D-07 | 0.99999912400000 | 2.36522014D-02 |

CHARACTERISTICS FOR MODE 18

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 4.79997696D-06 | 0.99999520000230 | 1.03680000D-02 | 0.98963200000000 | 3.76505026D-01 |
| 4380.00 | 4.79997696D-06 | 0.99999520000230 | 2.10240000D-02 | 0.97897600000000 | 2.29462404D-01 |
| 6540.00 | 4.79997696D-06 | 0.99999520000230 | 3.13920000D-02 | 0.96860800000000 | 1.66278247D-01 |
| 8760.00 | 4.79997696D-06 | 0.99999520000230 | 4.20480000D-02 | 0.95795200000000 | 1.29600538D-01 |

CHARACTERISTICS FOR MODE 19

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 2.15997670D-06 | 0.99999784400023 | 2.16000000D-06 | 0.99999784000000 | 1.69427892D-01 |
| 4380.00 | 4.37999041D-06 | 0.99999562000096 | 4.38000000D-06 | 0.99999562000000 | 2.09384990D-01 |
| 6540.00 | 6.53999461D-06 | 0.99999346000214 | 6.54000000D-06 | 0.99999346000000 | 2.26554456D-01 |
| 8760.00 | 8.75999163D-06 | 0.99999124000384 | 8.76000000D-06 | 0.99999124000000 | 2.36521081D-01 |

CHARACTERISTICS FOR MODE 20

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | UNAVAILABILITY IMPORTANCE |
|---|---|---|---|---|---|
| 2160.00 | 2.15999770D-07 | 0.99999978400000 | 2.16000000D-07 | 0.99999978400000 | 1.69428056D-02 |
| 4380.00 | 4.37999040D-07 | 0.99999956200001 | 4.38000000D-07 | 0.99999956200000 | 2.09385403D-02 |
| 6540.00 | 6.53999860D-07 | 0.99999934600002 | 6.54000000D-07 | 0.99999934600000 | 2.26555125D-02 |
| 8760.00 | 8.75999616D-07 | 0.99999912400004 | 8.76000000D-07 | 0.99999912400000 | 2.36522014D-02 |

**********
****RELIABILITY ANALYSIS FOR THE TOP EVENT****
**********

| TIME | UNAVAILABILITY | AVAILABILITY | EXPECTED NUMBER OF FAILURES | RELIABILITY | FAILURE RATE |
|---|---|---|---|---|---|
| 2160.00 | 1.27447726D-05 | 0.9999872512274 | 1.03759488D-02 | 0.98962405120000 | 4.85402967D-06 |
| 4380.00 | 2.09183591D-05 | 0.9999790816409 | 2.10401184D-02 | 0.97895988160000 | 4.90686506D-06 |
| 6540.00 | 2.88471371D-05 | 0.9999711328629 | 3.14160672D-02 | 0.96858393280000 | 4.95938828D-06 |
| 8760.00 | 3.70367055D-05 | 0.9999629632945 | 4.20802368D-02 | 0.95791976320000 | 5.01455521D-06 |

# APPENDIX IV

## UNCERTAINTY ANALYSIS OF TOP EVENT, LOSS OF CAPABILITY TO SHUT DOWN, RELIABILITY CHARACTERISTICS PERFORMED BY SAMPLE

The first five pages of results represent a 90 percent likelihood that the input data are within plus or minus a factor of 10 of the assigned value. The remaining five pages represent a 90 percent likelihood that the input data are within plus or minus a factor of 100 of the assigned value.

********** SAMPLE-A CODE FOR DETERMINING THE DISTRIBUTION AND CONFIDENCE LIMITS BY SIMULATION **********

CRBRP PPS

FUNCTION NO. 1

INPUT MEDIANS AND 90% ERROR FACTORS

( 1) 4.8000E-06 1.0000E 01

MEDIAN POINT VALUE FOR SYSTEM IS 4.8000E-06

OUTPUT EVALUATIONS. SAMPLE SIZE = 1200 ACCURACY ON 95 PER CENT CONFIDENCE INTERVAL = 1.0 PER CENT

DISTRIBUTION PARAMETERS. MEAN = 1.3380E-05 STANDARD DEVIATION = 3.0307E-05

DISTRIBUTION CONFIDENCE LIMITS

| CONFIDENCE (PER CENT) | FUNCTION VALUE |
|---|---|
| 0.5 | 1.2431E-07 |
| 1.0 | 2.3655E-07 |
| 2.5 | 3.5740E-07 |
| 5.0 | 4.7601E-07 |
| 10.0 | 7.7253E-07 |
| 20.0 | 1.4152E-06 |
| 25.0 | 1.7280E-06 |
| 30.0 | 2.1923E-06 |
| 40.0 | 3.2342E-06 |
| 50.0 | 4.5800E-06 |
| 60.0 | 6.5439E-06 |
| 70.0 | 1.0146E-05 |
| 75.0 | 1.2980E-05 |
| 80.0 | 1.6634E-05 |
| 90.0 | 3.1457E-05 |
| 95.0 | 5.2719E-05 |
| 97.5 | 7.7944E-05 |
| 99.0 | 1.2720E-04 |
| 99.5 | 1.9268E-04 |

********** SAMPLE-A CODE FOR DETERMINING THE DISTRIBUTION AND CONFIDENCE LIMITS BY SIMULATION **********

CPHRP PPS

FUNCTION NO. 1

INPUT MEDIANS AND 90% ERROR FACTORS

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ( 1) | 1.0000E-10 | 1.0000E 01 | ( 2) | 1.0000E-10 | 1.0000E 01 | ( 3) | 1.0000E-10 | 1.0000E 01 | ( 4) | 1.0000E-10 | 1.0000E 01 |
| ( 5) | 1.0000E-10 | 1.0000E 01 | ( 6) | 1.0000E-10 | 1.0000E 01 | ( 7) | 1.0000E-10 | 1.0000E 01 | ( 8) | 1.0000E-10 | 1.0000E 01 |
| ( 9) | 1.0000E-10 | 1.0000E 01 | (10) | 1.0000E-11 | 1.0000E 01 | (11) | 1.0000E-11 | 1.0000E 01 | (12) | 1.0000E-11 | 1.0000E 01 |
| (13) | 5.0000E-11 | 1.0000E 01 | (14) | 5.0000E-10 | 1.0000E 01 | (15) | 5.0000E-10 | 1.0000E 01 | (16) | 5.0000E-10 | 1.0000E 01 |
| (17) | 1.0000E-10 | 1.0000E 01 | (18) | 4.8000E-06 | 1.0000E 01 | (19) | 1.0000E-09 | 1.0000E 01 | (20) | 1.0000E-10 | 1.0000E 01 |

MEDIAN POINT VALUE FOR SYSTEM IS 1.2749E-05

OUTPUT EVALUATIONS. SAMPLE SIZE = 1200 ACCURACY ON 95 PER CENT CONFIDENCE INTERVAL = 1.0 PER CENT

DISTRIBUTION PARAMETERS. MEAN = 3.3596E-05 STANDARD DEVIATION = 3.3835E-05

DISTRIBUTION CONFIDENCE LIMITS

| CONFIDENCE (PER CENT) | FUNCTION VALUE |
|---|---|
| 0.5 | 6.1671E-06 |
| 1.0 | 7.4178E-06 |
| 2.5 | 8.6750E-06 |
| 5.0 | 1.0194E-05 |
| 10.0 | 1.2526E-05 |
| 20.0 | 1.6029E-05 |
| 25.0 | 1.7364E-05 |
| 30.0 | 1.8559E-05 |
| 40.0 | 2.1586E-05 |
| 50.0 | 2.4757E-05 |
| 60.0 | 2.9640E-05 |
| 70.0 | 3.4643E-05 |
| 75.0 | 3.8462E-05 |
| 80.0 | 4.3123E-05 |
| 90.0 | 6.0454E-05 |
| 95.0 | 8.0941E-05 |
| 97.5 | 1.1336E-04 |
| 99.0 | 1.6804E-04 |
| 99.5 | 2.0656E-04 |

********** SAMPLE-A CODE FOR DETERMINING THE DISTRIBUTION AND CONFIDENCE LIMITS BY SIMULATION **********

CRARR PRS FUNCTION NO. 1

INPUT MEDIANS AND 99% ERROR FACTORS

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ( 1) | 1.0000E-10 | 1.0000E 01 | ( 2) | 1.0000E-10 | 1.0000E 01 | ( 3) | 1.0000E-10 | 1.0000E 01 | ( 4) | 1.0000E-10 | 1.0000E 01 |
| ( 5) | 1.0000E-10 | 1.0000E 01 | ( 6) | 1.0000E-10 | 1.0000E 01 | ( 7) | 1.0000E-10 | 1.0000E 01 | ( 8) | 1.0000E-10 | 1.0000E 01 |
| ( 9) | 1.0000E-10 | 1.0000E 01 | (10) | 1.0000E-11 | 1.0000E 01 | (11) | 1.0000E-11 | 1.0000E 01 | (12) | 1.0000E-11 | 1.0000E 01 |
| (13) | 5.0000E-11 | 1.0000E 01 | (14) | 5.0000E-10 | 1.0000E 01 | (15) | 5.0000E-10 | 1.0000E 01 | (16) | 5.0000E-10 | 1.0000E 01 |
| (17) | 1.0000E-10 | 1.0000E 01 | (18) | 4.0000E-06 | 1.0000E 01 | (19) | 1.0000E-09 | 1.0000E 01 | (20) | 1.0000E-10 | 1.0000E 01 |

MEDIAN POINT VALUE FOR SYSTEM IS 2.0919E-05

OUTPUT EVALUATIONS. SAMPLE SIZE = 1200 ACCURACY ON 95 PER CENT CONFIDENCE INTERVAL = 1.0 PER CENT

DISTRIBUTION PARAMETERS. MEAN = 5.5019E-05 STANDARD DEVIATION = 4.3619E-05

DISTRIBUTION CONFIDENCE LIMITS

| CONFIDENCE (PER CENT) | FUNCTION VALUE |
|---|---|
| 0.5 | 1.1655E-05 |
| 1.0 | 1.3370E-05 |
| 2.5 | 1.6207E-05 |
| 5.0 | 1.8851E-05 |
| 10.0 | 2.2159E-05 |
| 20.0 | 2.8785E-05 |
| 25.0 | [illegible]E-05 |
| 30.0 | 3.3053E-05 |
| 40.0 | 3.7575E-05 |
| 50.0 | 4.2640E-05 |
| 60.0 | 5.0056E-05 |
| 70.0 | 5.9064E-05 |
| 75.0 | 6.4099E-05 |
| 80.0 | 7.1609E-05 |
| 90.0 | 9.6500E-05 |
| 95.0 | 1.2647E-04 |
| 97.5 | 1.6610E-04 |
| 99.0 | 2.1703E-04 |
| 99.5 | 2.6608E-04 |

********** SAMPLE-A CODE FOR DETERMINING THE DISTRIBUTION AND CONFIDENCE LIMITS BY SIMULATION **********

CRRPP PBS FUNCTION NO. 1

INPUT MEDIANS AND 90% ERROR FACTORS

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ( 1) | 1.0000E-10 | 1.0000E 01 | ( 2) | 1.0000E-10 | 1.0000E 01 | ( 3) | 1.0000E-10 | 1.0000E 01 | ( 4) | 1.0000E-10 | 1.0000E 01 |
| ( 5) | 1.0000E-10 | 1.0000E 01 | ( 6) | 1.0000E-10 | 1.0000E 01 | ( 7) | 1.0000E-10 | 1.0000E 01 | ( 8) | 1.0000E-10 | 1.0000E 01 |
| ( 9) | 1.0000E-10 | 1.0000E 01 | (10) | 1.0000E-11 | 1.0000E 01 | (11) | 1.0000E-11 | 1.0000E 01 | (12) | 1.0000E-11 | 1.0000E 01 |
| (13) | 5.0000E-11 | 1.0000E 01 | (14) | 5.0000E-10 | 1.0000E 01 | (15) | 5.0000E-10 | 1.0000E 01 | (16) | 5.0000E-10 | 1.0000E 01 |
| (17) | 1.0000E-10 | 1.0000E 01 | (18) | 4.8000E-06 | 1.0000E 01 | (19) | 1.0000E-09 | 1.0000E 01 | (20) | 1.0000E-10 | 1.0000E 01 |

MEDIAN POINT VALUE FOR SYSTEM IS 2.8867E-05

OUTPUT EVALUATIONS. SAMPLE SIZE = 1200 ACCURACY ON 95 PER CENT CONFIDENCE INTERVAL = 1.0 PER CENT

DISTRIBUTION PARAMETERS. MEAN = 7.5863E-05 STANDARD DEVIATION = 5.6085E-05

DISTRIBUTION CONFIDENCE LIMITS

| CONFIDENCE (PER CENT) | FUNCTION VALUE |
|---|---|
| 0.5 | 1.6556E-05 |
| 1.0 | 1.8639E-05 |
| 2.5 | 2.2925E-05 |
| 5.0 | 2.5923E-05 |
| 10.0 | 3.1487E-05 |
| 20.0 | 4.0460E-05 |
| 25.0 | 4.3894E-05 |
| 30.0 | 4.6449E-05 |
| 40.0 | 5.2603E-05 |
| 50.0 | 5.9674E-05 |
| 60.0 | 6.9251E-05 |
| 70.0 | 8.1399E-05 |
| 75.0 | 8.9388E-05 |
| 80.0 | 1.0011E-04 |
| 90.0 | 1.3569E-04 |
| 95.0 | 1.7510E-04 |
| 97.5 | 2.2150E-04 |
| 99.0 | 2.9503E-04 |
| 99.5 | 3.3671E-04 |

********** SAMPLE-A CODE FOR DETERMINING THE DISTRIBUTION AND CONFIDENCE LIMITS BY SIMULATION **********

CWRRP PRS FUNCTION NO. 1

INPUT MEDIANS AND 90% ERROR FACTORS

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ( 1) | 1.0000E-10 | 1.0000E 01 | ( 2) | 1.0000E-10 | 1.0000E 01 | ( 3) | 1.0000E-10 | 1.0000E 01 | ( 4) | 1.0000E-10 | 1.0000E 01 |
| ( 5) | 1.0000E-10 | 1.0000E 01 | ( 6) | 1.0000E-10 | 1.0000E 01 | ( 7) | 1.0000E-10 | 1.0000E 01 | ( 8) | 1.0000E-10 | 1.0000E 01 |
| ( 9) | 1.0000E-10 | 1.0000E 01 | (10) | 1.0000E-11 | 1.0000E 01 | (11) | 1.0000E-11 | 1.0000E 01 | (12) | 1.0000E-11 | 1.0000E 01 |
| (13) | 5.0000E-11 | 1.0000E 01 | (14) | 5.0000E-10 | 1.0000E 01 | (15) | 5.0000E-10 | 1.0000E 01 | (16) | 5.0000E-10 | 1.0000E 01 |
| (17) | 1.0000E-10 | 1.0000E 01 | (18) | 4.8000E-06 | 1.0000E 01 | (19) | 1.0000E-09 | 1.0000E 01 | (20) | 1.0000E-10 | 1.0000E 01 |

MEDIAN POINT VALUE FOR SYSTEM IS 3.7037E-05

OUTPUT EVALUATIONS. SAMPLE SIZE = 1200 ACCURACY ON 95 PER CENT CONFIDENCE INTERVAL = 1.0 PER CENT

DISTRIBUTION PARAMETERS. MEAN = 9.7285E-05 STANDARD DEVIATION = 7.0305E-05

DISTRIBUTION CONFIDENCE LIMITS

| CONFIDENCE (PER CENT) | FUNCTION VALUE |
|---|---|
| 0.5 | 2.1593E-05 |
| 1.0 | 2.4011E-05 |
| 2.5 | 3.0245E-05 |
| 5.0 | 3.4280E-05 |
| 10.0 | 4.1065E-05 |
| 20.0 | 5.1895E-05 |
| 25.0 | 5.6250E-05 |
| 30.0 | 6.0327E-05 |
| 40.0 | 6.7748E-05 |
| 50.0 | 7.6761E-05 |
| 60.0 | 8.9459E-05 |
| 70.0 | 1.0537E-04 |
| 75.0 | 1.1702E-04 |
| 80.0 | 1.2782E-04 |
| 90.0 | 1.7218E-04 |
| 95.0 | 2.2885E-04 |
| 97.5 | 2.7401E-04 |
| 99.0 | 3.7683E-04 |
| 99.5 | 4.3998E-04 |

•••••••••••••••••••• SAMPLE-A CODE FOR DETERMINING THE DISTRIBUTION AND CONFIDENCE LIMITS BY SIMULATION ••••••••••••••••••••

CASRP PPS FUNCTION NO. 1

INPUT MEDIANS AND 90% ERROR FACTORS

( 1) 4.8000E-06 3.0000E 01

MEDIAN POINT VALUE FOR SYSTEM IS 4.8000E-06

OUTPUT EVALUATIONS. SAMPLE SIZE = 1200 ACCURACY ON 95 PER CENT CONFIDENCE INTERVAL = 1.0 PER CENT

DISTRIBUTION PARAMETERS. MEAN = 4.2914E-05 STANDARD DEVIATION = 2.1046E-04

DISTRIBUTION CONFIDENCE LIMITS

| CONFIDENCE (PER CENT) | FUNCTION VALUE |
|---|---|
| 0.5 | 2.1748E-08 |
| 1.0 | 5.6258E-08 |
| 2.5 | 1.0356E-07 |
| 5.0 | 1.5804E-07 |
| 10.0 | 3.2315E-07 |
| 20.0 | 7.9019E-07 |
| 25.0 | 1.0513E-06 |
| 30.0 | 1.5084E-06 |
| 40.0 | 2.6789E-06 |
| 50.0 | 4.4736E-06 |
| 60.0 | 7.5869E-06 |
| 70.0 | 1.4501E-05 |
| 75.0 | 2.0864E-05 |
| 80.0 | 3.0097E-05 |
| 90.0 | 7.7136E-05 |
| 95.0 | 1.6540E-04 |
| 97.5 | 2.9469E-04 |
| 99.0 | 6.0753E-04 |
| 99.5 | 1.1219E-03 |

********** SAMPLE-A CODE FOR DETERMINING THE DISTRIBUTION AND CONFIDENCE LIMITS BY SIMULATION **********

CHAIN PRA FUNCTION NO. 1

INPUT MEDIANS AND 90% ERROR FACTORS

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ( 1) | 1.0000E-10 | 3.0000E 01 | ( 2) | 1.0000E-10 | 3.0000E 01 | ( 3) | 1.0000E-10 | 3.0000E 01 | ( 4) | 1.0000E-10 | 3.0000E 01 |
| ( 5) | 1.0000E-10 | 3.0000E 01 | ( 6) | 1.0000E-10 | 3.0000E 01 | ( 7) | 1.0000E-10 | 3.0000E 01 | ( 8) | 1.0000E-10 | 3.0000E 01 |
| ( 9) | 1.0000E-10 | 3.0000E 01 | (10) | 1.0000E-11 | 3.0000E 01 | (11) | 1.0000E-1. | 3.0000E 01 | (12) | 1.0000E-11 | 3.0000E 01 |
| (13) | 5.0000E-11 | 3.0000E 01 | (14) | 5.0000E-10 | 3.0000E 01 | (15) | 5.0000E-10 | 3.0000E 01 | (16) | 5.0000E-10 | 3.0000E 01 |
| (17) | 1.0000E-10 | 3.0000E 01 | (18) | 4.8000E-06 | 3.0000E 01 | (19) | 1.0000E-09 | 3.0000E 01 | (20) | 1.0000E-10 | 3.0000E 01 |

MEDIAN POINT VALUE FOR SYSTEM IS 1.2749E-05

OUTPUT EVALUATIONS. SAMPLE SIZE = 1200 ACCURACY ON 95 PER CENT CONFIDENCE INTERVAL = 1.0 PER CENT

DISTRIBUTION PARAMETERS. MEAN = 1.0244E-04 STANDARD DEVIATION = 2.4949E-04

DISTRIBUTION CONFIDENCE LIMITS

| CONFIDENCE (PER CENT) | FUNCTION VALUE |
|---|---|
| 0.5 | 7.2630E-06 |
| 1.0 | 8.7040E-06 |
| 2.5 | 1.0140E-05 |
| 5.0 | 1.3706E-05 |
| 10.0 | 1.8526E-05 |
| 20.0 | 2.6232E-05 |
| 25.0 | 3.0141E-05 |
| 30.0 | 3.4217E-05 |
| 40.0 | 4.2128E-05 |
| 50.0 | 5.1330E-05 |
| 60.0 | 6.4534E-05 |
| 70.0 | 8.6264E-05 |
| 75.0 | 1.0176E-04 |
| 80.0 | 1.2230E-04 |
| 90.0 | 1.9494E-04 |
| 95.0 | 2.9757E-04 |
| 97.5 | 5.0517E-04 |
| 99.0 | 7.9037E-04 |
| 99.5 | 1.1757E-03 |

********** SAMPLE-A CODE FOR DETERMINING THE DISTRIBUTION AND CONFIDENCE LIMITS BY SIMULATION **********

CWARP PBS FUNCTION NO. 1

INPUT MEDIANS AND 90% ERROR FACTORS

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ( 1) | 1.0000E-10 | 3.0000E 01 | ( 2) | 1.0000E-10 | 3.0000E 01 | ( 3) | 1.0000E-10 | 3.0000E 01 | ( 4) | 1.0000E-10 | 3.0000E 01 |
| ( 5) | 1.0000E-10 | 3.0000E 01 | ( 6) | 1.0000E-10 | 3.0000E 01 | ( 7) | 1.0000E-10 | 3.0000E 01 | ( 8) | 1.0000E-10 | 3.0000E 01 |
| ( 9) | 1.0000E-10 | 3.0000E 01 | (10) | 1.0000E-11 | 3.0000E 01 | (11) | 1.0000E-11 | 3.0000E 01 | (12) | 1.0000E-11 | 3.0000E 01 |
| (13) | 5.0000E-11 | 3.0000E 01 | (14) | 5.0000E-10 | 3.0000E 01 | (15) | 5.0000E-10 | 3.0000E 01 | (16) | 5.0000E-10 | 3.0000E 01 |
| (17) | 1.0000E-10 | 3.0000E 01 | (18) | 4.8000E-06 | 3.0000E 01 | (19) | 1.0000E-09 | 3.0000E 01 | (20) | 1.0000E-10 | 3.0000E 01 |

MEDIAN POINT VALUE FOR SYSTEM IS 2.0918E-05

OUTPUT EVALUATIONS. SAMPLE SIZE = 1200 ACCURACY ON 95 PER CENT CONFIDENCE INTERVAL = 1.0 PER CENT

DISTRIBUTION PARAMETERS. MEAN = 1.6639E-04 STANDARD DEVIATION = 2.9900E-04

DISTRIBUTION CONFIDENCE LIMITS

| CONFIDENCE (PER CENT) | FUNCTION VALUE |
|---|---|
| 0.5 | 1.1953E-05 |
| 1.0 | 1.5126E-05 |
| 2.5 | 1.9797E-05 |
| 5.0 | 2.4352E-05 |
| 10.0 | 3.3854E-05 |
| 20.0 | 4.8117E-05 |
| 25.0 | 5.5593E-05 |
| 30.0 | 6.0840E-05 |
| 40.0 | 7.4738E-05 |
| 50.0 | 9.2350E-05 |
| 60.0 | 1.1197E-04 |
| 70.0 | 1.4630E-04 |
| 75.0 | 1.7727E-04 |
| 80.0 | 2.1229E-04 |
| 90.0 | 3.3446E-04 |
| 95.0 | 4.9687E-04 |
| 97.5 | 7.3109E-04 |
| 99.0 | 1.1945E-03 |
| 99.5 | 1.5600E-03 |

********** SAMPLE-A CODE FOR DETERMINING THE DISTRIBUTION AND CONFIDENCE LIMITS BY SIMULATION **********

CRARP PPS

FUNCTION NO. 1

INPUT MEDIANS AND 90% ERROR FACTORS

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ( 1) | 1.0000E-10 | 3.0000E 01 | ( 2) | 1.0000E-10 | 3.0000E 01 | ( 3) | 1.0000E-10 | 3.0000E 01 | ( 4) | 1.0000E-10 | 3.0000E 01 |
| ( 5) | 1.0000E-10 | 3.0000E 01 | ( 6) | 1.0000E-10 | 3.0000E 01 | ( 7) | 1.0000E-10 | 3.0000E 01 | ( 8) | 1.0000E-10 | 3.0000E 01 |
| ( 9) | 1.0000E-10 | 3.0000E 01 | (10) | 1.0000E-11 | 3.0000E 01 | (11) | 1.0000E-11 | 3.0000E 01 | (12) | 1.0000E-11 | 3.0000E 01 |
| (13) | 5.0000E-11 | 3.0000E 01 | (14) | 5.0000E-10 | 3.0000E 01 | (15) | 5.0000E-10 | 3.0000E 01 | (16) | 5.0000E-10 | 3.0000E 01 |
| (17) | 1.0000E-10 | 3.0000E 01 | (18) | 4.8000E-06 | 3.0000E 01 | (19) | 1.0000E-09 | 3.0000E 01 | (20) | 1.0000E-10 | 3.0000E 01 |

MEDIAN POINT VALUE FOR SYSTEM IS 2.8867E-05

OUTPUT EVALUATIONS. SAMPLE SIZE = 1200 ACCURACY ON 95 PER CENT CONFIDENCE INTERVAL = 1.0 PER CENT

DISTRIBUTION PARAMETERS. MEAN = 2.2856E-04 STANDARD DEVIATION = 3.6407E-04

DISTRIBUTION CONFIDENCE LIMITS

| CONFIDENCE (PER CENT) | FUNCTION VALUE |
|---|---|
| 0.5 | 1.7736E-05 |
| 1.0 | 2.2043E-05 |
| 2.5 | 2.9654E-05 |
| 5.0 | 3.4631E-05 |
| 10.0 | 4.3773E-05 |
| 20.0 | 6.8259E-05 |
| 25.0 | 7.8256E-05 |
| 30.0 | 8.7148E-05 |
| 40.0 | 1.0627E-04 |
| 50.0 | 1.2826E-04 |
| 60.0 | 1.5734E-04 |
| 70.0 | 2.0585E-04 |
| 75.0 | 2.4991E-04 |
| 80.0 | 3.0235E-04 |
| 90.0 | 4.6593E-04 |
| 95.0 | 7.1062E-04 |
| 97.5 | 1.0021E-03 |
| 99.0 | 1.5880E-03 |
| 99.5 | 1.9967E-03 |

********** SAMPLE-A CODE FOR DETERMINING THE DISTRIBUTION AND CONFIDENCE LIMITS BY SIMULATION **********

CRASP PPS

FUNCTION NO. 1

INPUT MEDIANS AND 90% ERROR FACTORS

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ( 1) | 1.0000E-10 | 3.0000E 01 | ( 2) | 1.0000E-10 | 3.0000E 01 | ( 3) | 1.0000E-10 | 3.0000E 01 | ( 4) | 1.0000E-10 | 3.0000E 01 |
| ( 5) | 1.0000E-10 | 3.0000E 01 | ( 6) | 1.0000E-10 | 3.0000E 01 | ( 7) | 1.0000E-10 | 3.0000E 01 | ( 8) | 1.0000E-10 | 3.0000E 01 |
| ( 9) | 1.0000E-10 | 3.0000E 01 | (10) | 1.0000E-11 | 3.0000E 01 | (11) | 1.0000E-11 | 3.0000E 01 | (12) | 1.0000E-11 | 3.0000E 01 |
| (13) | 5.0000E-11 | 3.0000E 01 | (14) | 5.0000E-10 | 3.0000E 01 | (15) | 5.0000E-10 | 3.0000E 01 | (16) | 5.0000E-10 | 3.0000E 01 |
| (17) | 1.0000E-10 | 3.0000E 01 | (18) | 4.8000E-06 | 3.0000E 01 | (19) | 1.0000E-09 | 3.0000E 01 | (20) | 1.0000E-10 | 3.0000E 01 |

MEDIAN POINT VALUE FOR SYSTEM IS 3.7037E-05

OUTPUT EVALUATIONS. SAMPLE SIZE = 1200 ACCURACY ON 95 PER CENT CONFIDENCE INTERVAL = 1.0 PER CENT

DISTRIBUTION PARAMETERS. MEAN = 2.9247E-04 STANDARD DEVIATION = 4.4261E-04

DISTRIBUTION CONFIDENCE LIMITS

| CONFIDENCE (PER CENT) | FUNCTION VALUE |
|---|---|
| 0.5 | 2.3680E-05 |
| 1.0 | 2.9453E-05 |
| 2.5 | 3.7560E-05 |
| 5.0 | 4.5675E-05 |
| 10.0 | 6.2758E-05 |
| 20.0 | 8.7991E-05 |
| 25.0 | 1.0034E-04 |
| 30.0 | 1.1244E-04 |
| 40.0 | 1.3786E-04 |
| 50.0 | 1.6705E-04 |
| 60.0 | 2.0380E-04 |
| 70.0 | 2.6952E-04 |
| 75.0 | 3.2459E-04 |
| 80.0 | 3.8274E-04 |
| 90.0 | 5.9900E-04 |
| 95.0 | 9.1439E-04 |
| 97.5 | 1.2379E-03 |
| 99.0 | 2.1039E-03 |
| 99.5 | 2.4650E-03 |

# VITA

Carroll Leon Cate has lived in Friendsville, Tennessee, since his birth on May 18, 1952. Primary and secondary education were obtained at Friendsville Academy from which he graduated in 1970. Bachelor of Science degrees were received from Carson-Newman College in 1974 and The University of Tennessee, Knoxville, in 1975. Mr. Cate then accepted a graduate research assistantship in the Department of Nuclear Engineering at The University of Tennessee, Knoxville. The Master of Engineering degree was granted in 1977.