NRC FORM 335 (6 83)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1 REPORT NUMBER (Assigned by TIDC, add Vol. No., if any)
NUREG/CR-4314
LA-10474-MS

2 Leave blank

3 TITLE AND SUBTITLE
A Brief Survey and Comparison of Common Cause Failure Analysis

4 RECIPIENT'S ACCESSION NUMBER

5 DATE REPORT COMPLETED
MONTH June YEAR 1985

6 AUTHOR(S)
Ray A. Waller

7 DATE REPORT ISSUED
MONTH August YEAR 1985

8 PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Los Alamos National Laboratory
Los Alamos, NM 87545

9 PROJECT/TASK/WORK UNIT NUMBER

10 FIN NUMBER
A7225

11 SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Division of Risk Analysis and Operations
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

12a TYPE OF REPORT

12b PERIOD COVERED (Inclusive dates)

13 SUPPLEMENTARY NOTES

14 ABSTRACT (200 words or less)

This paper presents a brief survey of methods and a list of references for analyzing common cause (mode) failures. Implicit models, explicit modeling techniques, and computer aids are included in the discussion. It is suggested that although current trends are emphasizing development of explicit models, a realistic assessment of data availability will force continued use of implicit or hybrid models in the immediate future.

15a KEY WORDS AND DOCUMENT ANALYSIS
common cause failure modes
common cause survey

15b DESCRIPTORS

16 AVAILABILITY STATEMENT
Unlimited

17 SECURITY CLASSIFICATION (This report)
Unclassified

18 NUMBER OF PAGES

19 SECURITY CLASSIFICATION (This page)
Unclassified

20 PRICE
$

NUREG/CR-4314
LA-10474-MS

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

A Brief Survey and Comparison of Common Cause Failure Analysis

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NUREG/CR-4314
LA-10474-MS

AN, R4, RG, and XA

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Manuscript submitted: June 1985
Date published: June 1985

Prepared for
Division of Risk Analysis
Office of Nuclear Regulatory Research
US Nuclear Regulatory Commission
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NRC FIN No. A7225-5

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A BRIEF SURVEY AND COMPARISON OF
COMMON CAUSE FAILURE ANALYSIS

by

Ray A. Waller

ABSTRACT

This paper presents a brief survey of methods and a list of references for analyzing common cause (mode) failures. Implicit models, explicit modeling techniques, and computer aids are included in the discussion. It is suggested that although current trends are emphasizing development of explicit models, a realistic assessment of data availability will force continued use of implicit or hybrid models in the immediate future.

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1. INTRODUCTION

System performance can be adversely affected by simultaneous failure (failures resulting from common cause, common defect, etc.) of two or more components. Many performance measures assume independent failures and thus tend to overestimate the true system performance when dependent (simultaneous) failures occur. The following quote from Evans (1975) illustrates this point.

> As a simple example, suppose the failure probability of a part is 10^{-6} under virtually all conditions, but is unity under a very rare, bad condition which occurs with probability 10^{-8}. The unconditional unreliability of the single part is still roughly 10^{-6} (the rare condition is unimportant). But for parallel redundancy (2 parts), the unconditional item-unreliability is 10^{-8}--the rare, bad condition dominates--not 10^{-12} as in the simple-minded calculation. This is a common-mode failure, and it'll kill your system every chance it gets.

Much literature has addressed the problems of analyzing the performance of dependent systems over the past 15 to 20 years. The references at the end of this paper indicate the breadth of activities reported on under terms such as common cause failure (CCF), common mode failure (CMF), multiple failures, dependent failures, and simultaneous failures. Smith and Watson (1980) provide a discussion of the various definitions used in describing multiple failures.

Gangloff (1975) and Dhillon (1979) have listed categories of simultaneous failures to include equipment design deficiency, operations and maintenance errors, external normal environment, external catastrophic environment, common manufacturer, common external power supply, and functional deficiency. This list is an indicator of the difficulties that multiple failures present to any analyst trying to quantify system performance. Note that the causes of multiple failures can be associated with such disparate items as design, operations, maintenance, environment, manufacture, common power, and function. The human factors and elements of nature included in these items are two things that greatly complicate the analysis of common cause failures. When these factors are combined with a large number of dependencies that may occur when modeling real systems, we can start to identify with the challenges confronting the analyst.

Numerous techniques have been presented for analyzing CCF. Attempts to model dependencies through fault-tree and event-tree analyses have provided insights to the problems (see Levine and Vesely 1976). Classification of failure modes as potential sources of CCFs has provided valuable information to both system designers and analysts.

Jacobs (1970) indicated a struggle by common cause analysts to develop quantitative methods, with the long-term goal of providing quantitative inputs for use in reliability analyses. Years later, Green (1981) said that both qualitative and quantitative reliability analyses are needed to reduce CMF in both design and operation stages. Green presents a defensive strategy that includes feedback loops to be integrated into reliability and management programs. Crellin, Jacobs, and Smith (1984) propose a classification system involving categories of failures to avoid some of the difficulties associated with the definitions of CMF and CCF. These three papers show that the treatment of CCF analysis is still evolving. Further the papers state that CCF can dominate system unreliability unless properly analyzed.

In this paper we summarize some properties of various techniques proposed for analyzing CCF. Each method is developed to satisfy given criteria. However, one central issue is how to handle the conditional probabilities produced by dependent events in a given systems model. Evans (1975) indicates that no new theory is needed to analyze these dependencies because the concepts of conditional probabilities and conditional statistical independence are fully developed and widely used. Yet the problem persists because (1) most, if not all, of the necessary conditional probabilities are unknown and no operational data exists to provide credible estimates, and (2) the complexity and innate dependencies of even small real world systems make it difficult, if not impossible, to account for the necessary conditional probabilities. Analysts have diligently pursued a solution at various levels of sophistication. The discussion that follows presents an approximate technique for bounding the conditional probabilities, some techniques that are developed by specializing the work of Marshall and Olkin (1967), selected computerized analytic methods, and other proposed models for CCF.

2. BOUNDING METHODS

The Reactor Safety Study of the Nuclear Regulatory Commission, WASH 1400 (1975), recognized the potential seriousness of CCF and elected to handle the consequences by bounding techniques. If events $A_1, A_2, \ldots, A_n$ represent multiple failure resulting from a specific cause, the relevant question is as follows: What can we say about the magnitude of the joint probability $P(\bigcap_{i=1} A_i)$? By using various conditioning arguments, upper and lower bounds, say P_U and P_L, were obtained for use in system reliability analysis to study the impact of CCF on system performance. The geometric mean of these bounds provides an estimate of the CCF probability. Harris (1983) provides an excellent review of this proposed square-root bounding procedure including both the WASH 1400 rationale and summaries of critiques by Lewis (1978) and Easterling (1978).

Concerns regarding the square-root procedure are as follows: (1) The rationale is closely tied to one model, the lognormal. (2) Many subjective choices are made in the process of determining the bounds and bounding models; further, the analytic results are quite sensitive to these personal choices.

(3) Attempts to extend the procedure to other than lognormal models present difficulties in interpretation of the geometric mean (square root of the product) of two subjectively determined bounds.

In summary, the square-root bounding technique should not be used without extensive study of the proposed model and system. Harris (1983) discusses an application to redundant systems that can serve as an example for investigating the performance in studying other systems.

A bounding method for the failure rate of catastrophic shocks is given by Apostolakis (1976) and discussed in Sec. 3.6.

3. MARSHALL AND OLKIN STRESS-RELATED METHODS

Marshall and Olkin (1967) presented some derivations of multivariate exponential distributions based on shock models. Various authors have addressed the CCF analysis problems through methods that are closely related to their work. Some methods include a fatal shock assumption. Section 3 discusses a selection of these methods.

3.1. Beta (β) Factor Model

Although not directly derived from the Marshall and Olkin (1967) work, the β-factor model presented by Fleming (1975) shares the assumption that time-to-failure is an exponential variable and that the shock for CCF is sufficient for total system failure. Further, Fleming and Raabe (1978) have shown the equivalence of the Marshall-Olkin and β-factor models for two units.

The development assumes two types of failures--individual or common. Suppose that λ is the failure intensity for the system. If λ_1 is the intensity of individual failures and if λ_2 is the intensity of common failures, then Fleming (1975) defines the β-factor to be $\beta = \lambda_2/(\lambda_1+\lambda_2) = \lambda_2/\lambda$. Thus, β is a proportion of CCF and is a unitless number in [0,1]. Further, the case $\beta = 0$ corresponds to all failures being independent and the case $\beta = 1$ represents the case where all failures are CCFs and the system operates as a single unit.

Examples of the β-factor model are provided by Fleming and Hannaman (1976), Dhillon and Proctor (1977), Edwards and Watson (1979), and Harris (1983).

The only real modeling constraint on the β-factor model is the limitation exhibited by the restricted flexibility of any one-parameter model. Practical application is another matter in that operational data are needed to estimate the parameter β. Any available data can be used in the estimation process;

however, failure reports typically don't provide the detail necessary to estimate the failure rates λ, λ_1, and λ_2. Thus, engineering judgment and other subjective information are used in many analyses.

3.2. The Binomial Failure Rate Model

Vesely (1977) develops a specialization of the Marshall and Olkin (1967) results for instantaneously repairable systems. Atwood (1980b) presents an extended discussion of the model and treats statistical inference issues.

Whereas the β-factor model agrees with the Marshall-Olkin model for two units, the binomial failure rate (BFR) model is a Marshall-Olkin specialization for two or more units.

Given a system of m components, there is one way that all components work, m ways that one component can fail, and (2^m-m-1) ways that two or more components can fail simultaneously. Thus the CCF rate, Λ, is given by the sum of the failure rates for 2, 3, ..., m simultaneous failures. Each component acts as a Bernoulli variable and is assumed to have a constant probability of failure, p, resulting from the common cause.

Application of the BFR method requires estimates of the parameters Λ and p. Thus, applicability of the BFR approach depends on the type, quality, and quantity of available data. If sufficient data exist to estimate the parameters, then the two-parameter BFR method provides greater flexibility to model reality than does the one-parameter β-factor model.

Vesely (1977) provides an example using data to model and analyze the reactor scram system for boiling water reactors. Atwood and Stevenson (1982), Atwood (1980a), and Stevenson and Atwood (1983) provide extensive data and analyses pertaining to diesel generators, pumps, and valves, respectively. Other discussions of the BFR procedure are given in the PRA Procedures Guide (1983), Edwards and Watson (1979), and Harris (1983). A comparison of the β-factor and BFR models is given in the PRA Procedures Guide.

3.3. C-Factor Model

The C-factor was proposed as an alternative to the one-parameter β-factor model by Evans, Parry, and Wreathall (1982, 1983) for use in the Ringhals 2 Probabilistic Safety Study as discussed by Gyllenbaga, Johnson, and Lilja (1983).

The C-factor is defined as the ratio of the intensity of CCFs (λ_2 in the definition of β) to the intensity of independent failures (λ_1 in the definition

of β). Thus there is a one-to-one relationship between the definition of the C-factor and that of the β-factor, given by

$$C = \frac{\beta}{1-\beta} \quad .$$

The principal difference between the β- and C-factor models is in the estimation of the intensity of the common cause shock process. In their estimate of the number of common cause failures in a historical data base for a given component type [such as licensee event reports (LERs)], Evans et al. (1982, 1983) include both observed multiple failures for common cause and individual failures that they judge to be potential CCFs (i.e., there were not actual multiple failures only because additional components were not demanded). More controversially, their estimate of the population exposure to common cause shocks is the number of component demands or the total component running time, whereas in the estimation of β-factors, system demands or running time are generally required. Evans et al. assert that because the number of true system demands (at least for standby systems) is negligible, and also difficult to determine, theirs is a better estimate of population exposure. Picard, Lowe, and Garrick (1983) have shown that unless one assumes that redundant components are not examined following the failure of one component, which seems improbable, the estimator of Evans et al. seriously underestimates the probability of system failure. They conclude that if the data are interpreted correctly (which probably means including potential common cause failures) the beta factor model estimate of the system failure rate will always correspond with the system data, subject to the limitations of a single-parameter model.

3.4. Common Load Model

Mankamo (1977) presents a model that assumes independent and identically distributed resistances, R_i, for each of m components, together with an independent random stress, S, acting on all components, and determines the probability of failure of exactly k = 1, 2, ..., m components. Of interest in CCF analysis is the set of probabilities associated with $k \geq 2$. Illustrations of the procedure are provided by Mankamo for assumed normal or lognormal models for both R and S. Also developed are indices to indicate tendency toward (strength of) CCF for components. A measure of "effective redundancy" or "loss in redundancy" for systems susceptible to CCF is proposed.

Edwards and Watson (1979) and Harris (1983) provide further discussion of the Mankamo Common Load Model. One idea discussed is the development of a measure of redundancy. They discuss Mankamo's proposal to define parameter n_k such that $P_m(k) = [P_m(1)]nk$, where $P_m(i)$ denotes the probability of i failures when m components are subjected to a random stress, S. Then n_k represents effective redundancy, whereas $(m - n_k)$ represents a loss in redundancy resulting from common failures. See Edwards and Watson (1979) for a table of values for n_k such that $P_m(k) = [P_m(1)]^{n_k}$.

This model requires many types of data. First, data are required to estimate models or parameters of assumed models for R and S for all different combinations of resistance and stress that are of interest. Second, extensive stress test data would be needed to check probabilities of k simultaneous failures to verify the applicability of the assumed models.

3.5. Extended Common Load Model

Harris (1983) offers an extension of Mankamo (1977) by considering the number of shocks received in a time internal (0,T) along with Mankamo's assumptions of a random magnitude for each shock received and by associating a random variable for the resistance of each component.

Harris (1983) suggests that the calculation of simultaneous failure probabilities may be of interest under the following specializations of the foregoing assumptions: (1) building on a model given in Church and Harris (1970) where resistances for the components are assumed known; (2) assuming and modeling "wear out" for the components by studying the physical characteristics of the components; and (3) assuming and modeling a "degrading effect" for the components as each shock is received. An example of this extended common load model for known resistances, exponentially distributed waiting times between shocks, and independently and exponentially distributed shock magnitudes is given.

3.6. Shock Model

Apostolakis (1975a, 1975b, and 1976) develops a model for catastrophic (fatal) shocks. Thus each component fails independently or as a part of a complete (all-components) system failure. A constant failure rate of λ_{cm} is assumed for catastrophic failures that arrive according to a Poisson process independent of the assumed exponential time-to-failure model for each component. An important contribution here is the development of results that indicate when

common cause failures are significant contributors to a reliability analysis. Let λ denote the failure rate for each component; then the results as given in Apostalakis (1975a) are as follow: (1) If $\lambda_{cm} > \lambda$, the common mode system failure probability is always greater than the random cause failure probability for all time, t. (2) If $\lambda_{cm} < \lambda$, there exists a time T, such that for $t < T$ the common mode system failure probability is dominant, whereas for $t > T$ the random cause failure probability dominates. (3) If $\lambda_{cm} < \lambda$, then for each mission time T_i, a useful maximum for the degree of redundancy is given by

$$n < \frac{\log(\lambda_{cm} T_i)}{\log(\lambda T_i)}$$

so long as $\lambda T_i < 0.1$. Resources for providing redundancy beyond this point can better be used to decrease the potential for CCF.

4. COMPUTER AIDES FOR CCF ANALYSIS

Computer assistance in CCF analysis has taken two forms. Some efforts have been devoted to the efficient and accurate evaluation of the joint and conditional probabilities associated with CCF analysis, whereas other activities have modified and developed techniques to exploit fault-tree structure for identification of common causes.

Corynen (1983) presents the $\Sigma\Pi$ (SIGMA-PI) method for calculating joint probabilities efficiently. Exact solutions can be computed for many complex problems, and approximate methods with specified accuracy can be provided for other cases. The $\Sigma\Pi$ method is based on a multiplicative operator, Π, for modeling the probability of the joint occurrence of conditionally independent events and an additive operator, Σ, for summing the probabilities of mutually exclusive events.

The PRA Procedures Guide (1983) discusses several programs for analyzing fault trees in support of a CCF analysis. Included are SETS by Worrell and Stack (1977, 1978); BACFIRE II by Rooney and Fussell (1978); GO by Gately and Williams (1978a, 1978b); COMCAN II by Rasmuson et al. (1979); and WAMCOM by Putney (1981). These bookkeeping aids help to identify and catalog causes (modes) of failures. The difficulty is to assure that the cut-sets, fault-trees, and other model descriptors are complete as the output of any code can be

only as good as the model being analyzed. Thus, it is important that the analyst include all dependencies in the model and that all potential common cause (mode) failures be available to the code.

Thaggert, Ingram, and Wood (1983) discuss the code FRANCALC, which is intended to be used to construct explicit models of conditional probabilities. Elerath and Ingram (1979) also treat dependencies in reliability analyses.

5. OTHER CCF ANALYSES

Vaurio (1980) has discussed availability with common cause and undetected failures. Here the effect of initial testing and random CCF on unavailability is addressed. He also proposes some explicit models for analyzing unavailability in the presence of CMF. His approach is to introduce pseudocomponents with constant unavailability in series with the system. Two computer codes, ICARUS [Vaurio and Sciaudone (1979)], and a modification of FRANTIC [Vesely and Goldberg (1977)], are used in the analysis.

Lindley and Singpurwalla (1984) have developed some multivariate distributions having Pareto marginal distributions. These models permit the analytic introduction of environmental factors (constraints) that affect CCF.

Campbell and Ellison (1984) provide a 13-step procedure for analyzing CCF. The following list of activities gives a mix of qualitative and quantitative inputs to a CCF analysis.

Step 1. Prepare component lists for each system fault-tree.

Step 2. Identify secondary failure susceptibilities and the special conditions for each component failure.

Step 3. Identify vulnerability locations in the plant for each component with assigned generic susceptibilities.

Step 4. Define root-cause events for the qualitative dependent failure analysis.

Step 5. Construct domains for the location of dependent root-cause events.

Step 6. Prepare computer program input describing the fault-trees, component lists, susceptibilities, special conditions, physical locations, root-cause events, and event domains.

Step 7. Identify the potentially dependent failure in each accident sequence.

Step 8. Determine frequencies of root-cause events.

Step 9. Determine conditional probabilities of component failures.

Step 10. Determine the conditions of root-cause events to accident sequence frequencies.

Step 11. Quantify the location-dependent common cause candidates.

Step 12. Sum the contributions to accident sequence frequencies.

Step 13. Summarize the task products for task report.

Reference to this 13-step procedure is made in the next section to illustrate problem areas and needs of CCF analysis that still exist today.

6. CONCLUDING REMARKS

The past fifteen years have produced much interest in and activity directed toward defining, understanding, modeling, and analyzing common cause failures. Yet there is a great need to devote more effort to better understand and analyze this important factor in the measuring and studying of system performance. Focusing on acceptable definitions and characteristics of solutions and building useful data systems may be starting points.

6.1. Definitions

Much effort has been devoted to defining and characterizing the elements of common-cause and multiple-failure events. Smith and Watson (1980) and Crellin, Jacobs, and Smith (1984) present various definitions and classification systems; yet there remains a great deal of subjectivity and interpretation in the meaning of terms related to CCF analysis.

In the Campbell and Ellison (1984) 13-step procedure given above, Steps 1, 2, and 3 require great effort in identifying primary and secondary failure susceptibilities. It then follows in Step 4 for the analyst to identify the dependency structure so that potential common cause failures can be catalogued. With this tedious and laborious activity, it is easy to see how important the basic definitions of CCF and the interpretations of some of them are in the qualitative portion of the analysis. Clearly, there is much subjectivity in Steps 1-4. The quantitative work in Steps 8-12 is strongly dependent on both the accuracy and completeness of the preceding qualitative steps and the availability of relevant data for analysis.

The developers and advocates for the various proposed methodologies are confident that they understand and have effectively communicated the definitions

used in their work. However, it is our experience that a great deal of confusion remains. Some methods seem to confuse and interchange component data with system data within the definitions. The role of redundancy in counting failures provides a potential misunderstanding of terms used in the different methods. The extension of methods from systems of two components to systems involving more than two components provides a third opportunity for different interpretations. Resolution of differences among terminologies and standardized definitions are necessary for comparative analyses of CCF methods.

6.2. Desirable Characteristics

The variety of methods surveyed in this paper exhibit many diverse characteristics. Yet the analysts have not evaluated these properties. Thus, a corrected effort directed toward the development and categorization of necessary and desirable characteristics for any method of CCF analysis has the potential to yield significant benefits.

One desirable characteristic for a CCF analytic solution is the dependence on parameters that are interpretable by system designers and estimable by reliability analysts. Both the β-factor and BFR models illustrate this property.

A second desirable characteristic of a CCF analytic solution is an indication of the amount of dependency in a given system. Further, an indication of how much of this dependency can be designed out of the system is helpful. The method of Apostolakis (1975a, 1975b, 1976) contains such an index.

Familiarity with a method will stimulate further research and refinement of various models. The β-factor model is presented in the text book by Dhillon and Singh (1981). The book by Henley and Kumamoto (1981) presents qualitative analyses and quantitative techniques for estimating failure rates in CCF. Having methods made readily available is desirable in that new ideas and applications provide a better understanding of the capabilities and limitations of each analytic technique.

6.3. Data Systems

Data requirements tend to be the dominant constraint in any CCF analysis. The PRA Procedures Guide (1983) addresses that problem and indicates that the need is for system-level operational data, whereas most current data systems record component-level data. This paucity of relevant data will remain a serious constraint on CCF analysis for some time.

Proper classification of data is another major concern. For example, is sufficient subjectivity in interpretation of records such as LERs to make repetition of failure causes unlikely under independent evaluations? Many data sources leave room for interpretations by individual data coders and analysts. Further, the underlying assumptions of the proposed methods vary significantly. For example, one method may assume that any CCF is fatal to the system, whereas another method assumes that only the potential for random CCF exists, and a third method assumes that the potential for design-induced CCF is nonexistent. Clearly, the subjectivity induced through assumptions in current models supplements the subjectivity in data interpretation.

Edwards and Watson (1979) discuss CCF data sources that include aircraft systems, US diesel operators, prototype reactors, French reactors, chemical plants, German reactors, US nuclear reactor systems, and other material taken from the WASH 1400 Reactor Safety Study (1975). Studies that integrate the information from these sources with the relevent questions of interest to system designers, performance analysts, and decision makers are potentially beneficial.

Campbell (1984) describes work supported by the US Department of Energy to develop a Dependency Evaluation Data Base (DEDB). The intent is to design and populate a data base of operational data that is useful in modeling dependency causes, so-called explicit modeling. This work focuses on causes of dependencies and the development of explicit models. The report presents the following conclusions and recommendations for continuing an effort to develop a DEDB.

1. A goal of the DEDB is to supplement existing, principally component-focused, data sources by establishing an event-oriented data base. A primary concern here would be the classification of observed dependency events with respect to causes.
2. The only sources of data for a data base such as the DEDB are public records like the LERs, Unusual Occurrence Reports (UORs), or reviews of such reports. These narrative reports require interpretation and evaluation (often subjective) in order to produce input to any data base.
3. The information in the DEDB must necessarily include both coded and narrative forms. Otherwise, the degree of subjectivity in the data is such that the utility of the data base is suspect.

4. Coding causes present a real challenge to the development of the DEDB. No ideal classification scheme has been identified, and more than one factor usually contributes to any given CCF event.
5. Successful development of a DEDB will require the dedication of appropriate personnel and the methodical review and evaluation of many (thousands) narrative event reports. The effort is clearly a multiyear multiperson undertaking.

Another effort that may lead to the development of dependency data is the work of Crellin, Jacobs, and Smith (1984). It is expected that their data will be useful in analyses related to their proposed classification of failure categories.

To summarize, work dedicated to data collection with specific goals is an essential activity for furthering the cause of sound analytic CCF modeling and analysis. Further, the current trend in CCF analysis is toward the use of more explicit (conditional probability) CCF models. The data requirements are heaviest for such approaches, and the data base structures required for collecting, organizing, and analyzing these necessary data are not yet fully understood. Until such data bases are in place, the immediate CCF emphasis is likely to focus on either implicit CCF models or hybrid approaches. In hybrid approaches, explicit models are used in conjunction with parametric accelerated stress (shock) models as a means of overcoming the lack-of-explicit-data problem.

7. RECOMMENDATIONS

Much activity and interest exists in the area of analysis of common cause, common mode, and multiple failures. Yet it is not clear that significant progress is being made toward the understanding and resolution of these important issues. Thus, we make the following recommendations for use of the limited resources in the desire that the efforts become focused toward resolution of existing differences.

- Develop a standard terminology.
- Develop criteria for comparative assessments of proposed methodologies.
- Develop credible data bases designed to answer the relevant estimation questions raised by system designers, performance analysts, and decision makers.

8. ACKNOWLEDGMENT

Financial support for this work was provided by the Division of Risk Analysis, Office of Nuclear Regulatory Research, Nuclear Regulatory Commission, under Fin #A7225-5. This support along with the technical assistance of Richard Beckman, Maurice Bryson, Katherine Campbell, and Harry Martz is gratefully acknowledged.

REFERENCES

This list of references includes both those items referenced in the body of the paper and other relevant readings.

Apostolakis, G. E. (1975a), "On a Certain Class of potential Common-Mode Failures," Trans. Am. Nucl. Soc., 22, pp. 476-477.

Apostolakis, G. E. (1975b), "On the Reliability of Redundant Systems," Trans. Am. Nucl. Soc., 22, pp. 477-478.

Apostolakis, G. E. (1976), "The Effect of a Certain Class of Potential Common-Mode Failures on the Reliability of Redundant Systems," Nucl. Eng. Des., 36, pp. 123-133.

Apostolakis, G. E. and Bansal, P. P. (1977), "Effect of Human Error on the Availability of Periodically Inspected Redundant Systems," IEEE Trans. Reliab., Vol. R-26, No. 3.

Atwood, C. L. (1980a), "Common Cause and Individual Failure and Fault Rates for Licensee Event Reports for Pumps at U.S. Commercial Nuclear Power Plants," EGG-EA-5289, NUREG/CR-2098, EG&G Idaho, Inc., Idaho Falls, ID.

Atwood, C. L. (1980b), "Estimators for the Binomial Failure Rate Common Cause Model" EGG-EA-5112, NUREG/CR-1401, EG&G Idaho, Inc., Idaho Falls, ID.

Atwood, C. L. and Stevenson, J. A. (1982),"Common Cause Fault Rates for Diesel Generators: Estimates Based on Licensee Event Reports at U.S. Commercial Nuclear Power Plants 1976-1978," EGG-EA-5359, NUREG/CR-2099, EG&G Idaho, Inc., Idaho Falls, ID.

Atwood, C. L. and Switt, W. J. (1981), "User's Guide to BFR, a Computer Code Based on the BFR CCF Model," EGG-EA-5502, EG&G Idaho, Inc., Idaho Falls, ID.

Barlow, R. T., Hill, R. A. and O'Brien, J. F. (1978), "Probabilistic Evaluation of Failure Modes Leading to the Mispositioning of Certain ECCS Motor Operated Valves in Westinghouse NSS," IEEE Trans. Power Appar. Syst., PAS-97, pp. 358-361.

Bignell, V., Peters, G. and Pym, C. (1976), Catastrophic Failures, Open University Press, Deventer, Netherlands.

Billington, R., Medicherla, T. K. P. and Sachdev, M. S. (1978), "Common-Cause Outages in Multiple Circuit Transmission Lines," IEEE Trans. Reliab., R-27, pp. 128-131.

Block, H. W. (1975), "Continuous Multivariate Exponential Extensions," in Reliability and Fault Tree Analysis, SIAM, Philadelphia, PA, pp. 285-306.

Brown, S. and Martin, J. N. T. (1977), Human Aspects of Man-Made Systems, Open University Press, Deventer, Netherlands.

Burdick, G. R. (1977),"COMCAN--A Computer Code for Common-Cause Analysis," IEEE Trans. Reliab., R-26, pp. 100-102.

Cain, D. G. (1977), "Closing the Loop Summary-Equipment Qualification," Proceedings of the 1977 Environmental Technology Conference, Institute of the Environmental Sciences, IL 60058, pp. 434-437.

Campbell, K. (1984), "Data and Software for Explicit Reliability Modeling--Preliminary Report," Draft, Los Alamos National Laboratory, Los Alamos, NM.

Campbell, D. J. and Ellison, B.C. (1984), "Draft Dependent Failure Analysis Procedures Guide," JBF Associates, Inc., Knoxville, TN.

Cate, C. L., Wagner, D. P. and Fussell, J. B. (1977), "A Computer Aided Approach to Qualitative and Quantitative Common-Cause Failure Analysis for Complex Systems," Proceedings of the Eighth Pittsburgh Modelling and Simulation Conference, Instrument Society of America, Pittsburgh, pp. 25-29.

Chelapati, C. V. and Kennedy, R. P. (1972), "Probabilistic Assessment of Aircraft Hazard for Nuclear Plants," Nucl. Eng. Des., 19, pp. 333-364.

Chu, B. B. and Gaver, D. P. (1977), "A Stochastic Modelling for Common-Mode Failures of Repairable Redundant Systems," Conference Proceedings, Edited by J. B. Fussell and G. R. Burdick, SIAM, Philadelphia, PA.

Church, J. D. and Harris, B. (1970), "The Estimation of Reliability from Stress-Strength Relationship," Technometrics, 12, pp. 49-54.

Commonwealth Edison Company (1981), "Zion Probabilistic Safety Study," Chicago, IL.

Corcoran, W. R., Porter, N. J., Church, J. F., Cross, M. T. and Grinn, W. M. (1980), "The Critical Safety Functions and Plant Operation," presented at the International Conference on Current Nuclear Power Plant Safety Issues, Stockholm, Sweden, October 20-24.

Corynen, G. C. (1983), "Evaluating the Response of Complex Systems to Environmental Threats: The ΣΠ Method," UCRL-53399, Lawrence Livermore National Laboratory, Livermore, CA.

Crellin, G. L., Jacobs, I. M. and Smith, A. M. (1984), "A Study of Common Cause Failures, Phase I: A Classification System," EPRI NP-3383, Electric Power Research Institute, Palo Alto, CA.

Crooks, J. L. and Vissing, G. S. (1974), "Diesel-Generator Operating Experience at U.S. Nuclear Power Plants," DOE-ES-002, US Atomic Energy Commission, Washington, DC.

Daniels, H. E. (1945), "The Statistical Theory of the Strength of Bundles of Threads," Proceedings of the Royal Society of London, Ser. A. 183, pp. 405-435.

Dhillon, B. S. (1976), "A Modification to Fault Tree 'AND' Gate," Microelectron. Reliab., 15, pp. 625-626.

Dhillon, B. S. (1977), "A 4-Unit Redundant System with Common-Cause Failures," IEEE Trans. Reliab., R-26, pp. 373-374.

Dhillon, B. S. (1978), "Effects of Weibull Hazard Rate on Common-Cause Analysis of Reliability Networks," Microelectron. Reliab., 17, pp. 59-65.

Dhillon, B. S. (1978), "A k-out-of-N Three-State Device System with Common-Cause Failures," Microelectron. Reliab., 18, pp. 447-448.

Dhillon, B. S. (1978), "Optimal Maintenance Policy for Systems with Common-Cause Failures," Proceedings of the Ninth Pittsburgh Modelling and Simulation Conference, Instrument Society of America, Pittsburgh, PA.

Dhillon, B. S. (1978), "A Common-Cause Failure Availability Model," Microelectron. Reliab., 17, pp. 583-584.

Dhillon, B. S. (1978), "On Common-Cause Failures-Bibliography," Microelectron. Reliab., 18, pp. 533-534.

Dhillon, B. S. (1979), "A 4-Unit Redundant System with Common-Cause Failures," IEEE Trans. Reliab., R-28, p. 267.

Dhillon, B. S. and Proctor, C. L. (1977), "Common-Mode Failure Analysis of Reliability Networks," Proceedings of the Annual Reliability and Maintainability Symposium, IEEE, New York, pp. 404-408.

Dhillon, B. S., Sambhi, A. and Khan, M. R. (1979), "Common Cause Failure Analysis of a Three-State Device System," Microelectron. Reliab., 19, pp. 345-348.

Dhillon, B. S. and Singh, C. (1981), Engineering Reliability, John Wiley & Sons, New York.

Ditto, S. J. (1966), "Failures of Systems Designed for High Reliability," Nucl. Saf., 8, pp. 35-37.

Easterling, R. G. (1978), "Probabilistic Analysis of 'Common Mode Failures'," in "Probabilistic Analysis of Nuclear Reactor Safety, Vol. III," Proceedings of Topical Meeting, Newport Beach, CA.

Edwards, G. T. and Watson, I. A. (1979), "A Study of Common Mode Failures," SRD-R-146, United Kingdom Academic Energy Authority, Wigshaw Lane, Culcheth Warrington WA3 4NE.

Elerath, J. G. and Ingram, G. E. (1979), "Treatment of Dependencies in Reliability Analyses," Proceedings of the Annual Reliability and Maintainability Symposium, IEEE, New York, pp. 99-103.

Epler, E. P. (1970), "Common-Mode Failure Consideration in the Design of Systems for Protection and Control," Nucl. Saf., 11, pp. 323-327.

Epler, E. P. (1970), "The ORR Emergency Cooling Failures," Nucl. Saf., 11, pp. 323-327.

Epler, E. P. (1977), "Diversity and Periodic Testing in Defense Against Common-Mode Failures," Conference Proceedings, Society for Industrial and Applied Mathematics, Edited by J. B. Fussel and G. R. Burdick, Philadelphia, PA 19103.

Electric Power Research Institute (EPRI) (1982), "Frequency of Anticipated Transients," in "ATWS--A Reapprasial," Part 3, EPRI NP-2330, Electric Power Research Institute, Palo Alto, CA.

Evans, R. A. (1975), "Statistical Independence and Common-Mode Failures," IEEE Trans. Reliab., R-24, p. 289.

Evans, M. G. K., Parry, G. W. and Wreathall, J. (1982), "An Approach to the Quantification of Common Cause Failure in System Analysis," Draft, NUS Corp., Gaithersburg, MD.

Evans, M. G. K., Parry, G. W. and Wreathall, J. (1983), "On the Treatment of Common Cause Failures in Systems Analysis," Reliab. Eng., Vol. 9, No. 2.

Fleming, K. N. (1974), "A Reliability Model for Common Mode Failures in Redundant Safety Systems," GA-13284, General Atomic Co., San Diego, CA.

Fleming, K. N. (1975), "A Redundant Model for Common Mode Failures in Redundant Safety Systems," Proceedings of the Sixth Pittsburgh Annual Modelling and Simulation Conference, Instrument Society of America, Pittsburgh, PA, pp. 579-581.

Fleming, K. N. et al. (1975), "AIPA Risk Assessment Methodology," in "HTGR Accident Initiation and Progression Analysis Status Report," Vol. II, GA-A13617, General Atomic Co., San Diego, CA.

Fleming, K. N. and Hannaman, G. W. (1976), "Common Cause Failure Consideration in Predicting HTGR Cooling System Reliability," IEEE Trans. Reliab., R-25, pp. 171-177.

Fleming, K. N. and Hannaman, G. W. (1976), "Common Cause Failure Considerations in the Prediction of HTGR Cooling System Reliability," GA-A13658, General Atomic Co., San Diego, CA.

Fleming, K. N. and Raabe, P. H. (1978), "A Comparison of Three Methods for the Quantitative Analysis of Common Cause Failures," Proceedings of the ANS Nuclear Reactor Safety Division of Probabilistic Analysis of Nuclear Reactor Safety, Los Angeles, CA, May 8-10, 1978. American Nuclear Society, La Grange Park, IL.

Fleming, K. N., Mosleh, A. and Kelley, A. P. Jr. (1983), "On the Analysis of Dependent Failures in Risk Assessment and Reliability Evaluation," Nucl. Saf., 5, pp. 637-657.

Frederick, L. G. (1970), "An Analysis of Functional Common Mode Failures in G. E. BWR Protection and Control Instrumentation," NEDO-10189, General Electric Co., Sunnyvale, CA.

Fussell, J. B. and Burdick, G. R. (1977), Nuclear Systems Reliability Engineering and Risk Assessment, SIAM, Philadelphia, PA.

Gachot, B. (1977), "A Probabilistic Approach to Design for the ECCS of a PWR," Proceedings of the Annual Reliability and Maintainability Symposium, IEEE, New York, pp. 332-342.

Gangloff, W. C. (1971), "An Evaluation of Anticipated Operational Transients in Westinghouse Pressurized Water Reactors," WCAP 7486, Westinghouse Electric Coporation, Pittsburgh, PA.

Gangloff, W. C. (1972), "Common-Mode Failure Analysis is 'in'," Electron World, pp. 30-33.

Gangloff, W. C. (1975), "Common Mode Failure Analysis," IEEE Trans. Power Appar. Sys., PAS-94, pp. 27-30.

Gangloff, W. C. and Franke, T. (1974), "An Engineering Approach to Common-Mode Failure Analysis," Conference on the Development and Application of Reliability Techniques to Nuclear Plants, Liverpool, England.

Garrick, B. J., Gekler, W. C. and Pomrehn, H. P. (1975), "Some Aspects of Protective Systems in Nuclear Power Plants," IEEE Trans. Nucl. Sci., NS-12, pp. 22-30.

Gately, W. V. and Williams, R. L. (1978a), "GO Methodology-Overview," EPRI NP-765, Electric Power Research Institute, Palo Alto, CA.

Gately, W. V. and Williams, R. L. (1978b), "GO Methodology-System Reliability Assessment and Computer Code Manual," EPRI NP-766, Electric Power Research Institute, Palo Alto, CA.

Green, A. E. (1972), "Safety Assessment of Reactor Systems," Nucl. Saf., 15, No. 2.

Green, A. E. (1981), "The Reliability Assessment of Automatic Protective Systems for the Safety of Nuclear Reactors," Proceedings of the Annual Reliability and Maintainability Symposium, IEEE, New York, pp. 317-322.

Green, A. E. and Bourne, A. J. (1972), Reliability Technology, Wiley-Interscience, New York.

Green, A. E. and Bourne, A. J., "Safety Assessment with Reference to Automatic Protective Systems for Nuclear Reactors," UKAEA Report AHSB (S) R 117.

Gyllenbago, H., Johnson, G. and Lilja, T. (1983), "Treatment of Dependencies in Ringhals 1 & 2 Safety Studies," Workshop on Dependent Failure Analysis, Vasteräs, Sweden.

Hanauer, S. H. and Walker, C. S. (1968), "Design Principles of Reactor Protection Instrument Systems," ORNL-NSIC-51, Oak Ridge National Laboratory, Oak Ridge, TN.

Harris, B. (1983), "Stochastic Models for Common Failures of Components," Technical Report No. 27, Dept. of Statistics, Univ. of Wisconsin, Madison.

Hayden, K. C. (1975), "Common Mode Failure Mechanisims in Nuclear Plant Protection Systems, ORNL-TM-4984, Oak Ridge National Laboratory, Oak Ridge, TN.

Hayden, K. C. (1976), "Common-Mode Failure Mechanisms in Redundant Systems Important to Reactor Safety," Nucl. Saf., 17, pp. 686-693.

Henley, E. J. and Kumamoto, H. (1981), Reliability Engineering and Risk Assessment, Prentice-Hall, Inc., Englewood Cliffs, NJ.

Houghton, W. J., Joksimovie, V. and Emon, D. E. (1975), "Methods of Probabilistic Safety Analysis for Gas-Cooled Reactors," Trans. Am. Nucl. Soc., 21, pp. 210-217.

Institute of Electrical and Electronics Engineers (IEEE) (1975), "Guide to General Principles of Reliability Analysis of Nuclear Power Generating Station Protection Systems, IEEE Standard 352-1975, IEEE, New York.

Jacobs, I. M. (1970), "The Common-Mode Failure Study Discipline," IEEE Trans. Nucl. Sci., NS-17, pp. 594-598.

Jolly, M. E. and Wreathall, J. (1977), "Common-Mode Failures in Reactor Safety Systems", Nucl. Saf., Vol. 18, No. 5.

Kelley, A. P. and Stillwell, D. W. (1981), "Application and Comparison of the GO Methodology and Fault Tree Analysis," EPRI Research Project 818-3, Electric Power Research Institute, Palo Alto, CA.

Laceby, M. and Southcombe, G. (1977), "Concorde Reliability Programme and Results," Symposium on Quality and Reliability in Aerospace, Royal Aeronautical Society, England.

Lambert, H. E. (1975), "Fault Trees for Decision Making in Systems Analysis," UCRL-51829, Lawrence Livermore National Laboratory, Livermore, CA.

Lee, L. and Thompson, W. A. Jr. (1974), "Results on Failure Time and Pattern for the Series System," in Reliability and Biometry, SIAM, Philadelphia, PA.

Levine, S. and W. E. Vesely (1976), "Important Event-Tree and Fault-Tree Considerations in the Reactor Safety Study," IEEE Trans. Reliab., R-25, pp. 132-139.

Leverenz, F. L., Rumble, E. T. and Erdmann, E. (1975), "A Dependent-Event Model for Fault Trees," Trans. Amer. Nucl. Soc., 21, pp. 212-213.

Lewis, H. W. (1978), "Risk Assessment Review Group Report to the US Nuclear Regulatory Commission," NUREG/CR-0400, US Nuclear Regulatory Commission, Washington, DC.

"Licensee Event Reports," Office of Operations Evaluation, US Nuclear Regulatory Commission, Washington, DC.

Lindley, D. V. and Singpurwalla, N. D. (1984), "Multivariate Distributions for the Reliability of a System of Components Sharing a Common Environment," GWU/IRRA/TR-84/1, George Washington University, Washington, DC.

Mankamo, T. (1976), "Common Mode Failures," Sahkotekniikam Laborratorio, Technical Research Centre of Finland, Electrical Engineering Laboratory Report 18, Tiedonanto 31.

Mankamo, T. (1977), "Common Load Model, A Tool for Common Cause Failure Analysis," Sahkotekniikam Laborratorio, Technical Research Centre of Finland, Tiedonanto 31.

Mankamo, T. (1978), "Common Cause Failure of Reactor Pressure Components," in Reliability Problem of Reactor Pressure Components, Vol. I, pp. 125-136. International Atomic Energy Agency, Vienna.

Marshall, A. W. and Olkin, I. (1967), "A Multivariate Exponential Distribution," J. Am. Stat. Assoc., 62, pp. 30-44.

Philadelphia Electric Co. (1978), "Probabilistic Risk Assessment, Limerick Generating Station," Pocket Nos. 50-352, 50-353, US Nuclear Regulatory Commission, Washington, DC.

Picard, Lowe and Garrick, Inc. (1983), "Preliminary Review of the Ringhals 2 Probabilistic Safety Study," Swedish Nuclear Power Inspectorate, Stockholm, Sweden.

PRA Procedures Guide (1983), NUREG/CR-2300, Vol. 1, US Nuclear Regulatory Commission, Washington, DC.

Putney, B. (1981), "WAMCOM, Common-Cause Methodology Using Large Fault Trees," EPRI NP-1851, Electric Power Research Institute, Palo Alto, CA.

Rankin, J. P. (1973), "Sneak-Circuit Analysis," Nucl. Saf., 14, pp. 461-469.

Rankin, J. P. (1982), "Common Cause Hazard Analysis for Random Glitches," Proceedings of the Annual Reliability and Maintainability Symposium, IEEE, New York, pp. 1-4.

Rasmuson, D. M., Marshall, N. H., Wilson, J. R. and Burdick, G. R. (1979), "COMCAN II -- A Computer Program for Automated Common Cause Failure Analysis," TREE-1361, EG&G Idaho, Inc., Idaho Falls, ID.

Rooney, J. J. and Fussell, J. R. (1978), "BACFIRE II -- A Computer Program for Common Cause Failure Analysis for Complex Systems," University of Tennessee, Knoxville, TN.

Rubel, P. (1976), "Tiger in the Fault Tree Jungle," Proceedings of the Seventh Annual Pittsburgh Modelling and Simulation Conference, Pittsburgh Instrument Society of America, Pittsburgh, PA, pp. 1071-1082.

Scott, R. L. and Gallaher, R. B. (1977), "Annotated Bibliography of Safety Related Occurrences in Pressurized Water Nuclear Power Plants as Reported in 1976," ORNL/NUREG/NSIC-138, Oak Ridge National Laboratory, Oak Ridge, TN.

Sen, P. K. (1973), "An Asymptotically Efficient Test for the Bundle Strength of Filaments," J. Appl. Probab., 10, pp. 586-596.

Sen, P. K. (1973), "On Fixed Size Confidence Bounds for the Bundle Strength of Filaments," Annu. Stat., 1, pp. 526-537.

Shooman, M. (1968), Probabilistic Reliability: An Engineering Apprcach, McGraw Hill, New York.

Smith, A. M. and Watson, I. A. (1980), "Common Cause Failures--A Dilemma in Perspective," Proceedings of the Reliability and Maintainability Symposium, IEEE, New York, pp. 332-339.

Stevenson, J. A. and Atwood, C. L. (1983), "Common Cause Fault Rates for Valves," NUREG/CR-2770, EGG-EA-5485, EG&G Idaho, Inc., Idaho Falls, ID.

Taylor, J. R. (1974), "Design Error in Nuclear Power Plant," RISO-M-1742, Danish Atomic Energy Commission, Risø, Denmark.

Taylor, J. R. (1975), "Common Mode and Coupled Failures," RISO-M-1826, Danish Atomic Energy Commission, Risø, Denmark.

Taylor, J. R. (1975), "A Study of Failure Causes Based on U.S. Power Reactor Abnormal Occurrence Reports," in Reliability of Nuclear Power Plants, IAEA-SM-195/16, International Atomic Energy Association, Vienna, Austria.

Thaggert, H. L., Ingram, G. E. and Wood, A. P. (1983), "FRANCALC User's Manual: A Computer Program for Instantaneous and Average Unavailability Calculations," GEFR00600, General Electric, Sunnyvale, CA.

Varnado, G. B. and Ortiz, N. R. (1979), "Fault Tree Analysis for Vital Area Indentification," NUREG/CR-0809, SAND 79-0946, Sandia National Laboratories, Albuquerque, NM.

Varnado, G. B. and Haarman, R. A. (1980), "Vital Area Analysis for Nuclear Power Plants," Proceedings of the 21st Annual Meeting of the Institute of Nuclear Materials Management, Palm Beach, FL.

Varnado, G. B. et al. (1980), "Fault Tree Analysis Procedures for the Interim Reliability Evaluation Program," SAND 81-0062 (draft), Sandia National Laboratories, Albuquerque, NM.

Varnado, G. B. et al. (1981), "Fault Tree Analysis Using Modular Logic Models," Proceedings of the ANS/EWS Topical Meeting on Probabilistic Risk Assessment, September 20-24, Port Chester, NY. American Nuclear Society, La Grange Park, IL.

Vaurio, J. K. (1980), "Availability of Redundant Safety Systems with Common-Mode and Undetected Failures," Nucl. Eng. Des., 58, pp. 415-424.

Vaurio, J. K. and Sciaudone, D. (1979), ANL-79-87, Argonne National Laboratory, Argonne, IL.

Vesely, W. E. (1977), "Estimating Common-Cause Failure Probabilities in Reliability and Risk Analysis: Marshal-Olkin Specialization," Edited by J. B. Fussell and G. R. Burdick, Society for Industrial and Applied Mathematics, Philadelphia, PA 19103, pp. 314-341.

Vesely, W. E. and Goldberg, F. F. (1977), IEEE Trans. Reliab., R-26, p. 257ff.

Vesely, W. E., Goldberg, F. F., Roberts, N. H. and Haasl, D. F. (1981), "Fault Tree Handbook," NUREG-0492, US Nuclear Regulatory Commission, Washington, DC.

Vesely, W. E. and Johnson, J. W. (1978), "Common Mode Analysis of Valve Leakage Proceedings ANS Nuclear Reactor Safety Division of Probabilistic Analysis of Nuclear Safety, May 8-10, 1978, Los Angeles, CA. American Nuclear Society, La Grange Park, IL.

Volta, G. (1976), "The Common Mode Failure Analysis," CEC ISPRA, SR76, No. 8, Italy.

Wagner, D. P., Cate, C. L. and Fussell, J. B. (1977), "Common-Cause Failure Analysis Methodology for Complex Systems," Edited by J. B. Fussell and G. R. Burdick, Conference Proceedings, Society for Industrial and Applied Mathematics, 33 South 17 St., Philadelphia,PA 19013, U.S.A.

Wall, I. B. (1974), "Probabilistic Assessment of Flooding for Nuclear Power Plants," Nucl. Saf., 15, pp. 399-408.

Wall, I. B. (1974), "Probabilistic Assessment of Aircraft Risk for Nuclear Power Plants," Nucl. Saf., 15, pp. 276-284.

WASH-1270 (1973), "Anticipated Transient Without Scram for Water Cooled Power Reactors," US Atomic Energy Commission, Washington, DC.

WASH-1400 (1975), "Common Mode Failures - Bounding Techniques and Special Techniques," Appendix IV, NUREG-75/014, US Nuclear Regulatory Commission, Washington, D.C.

WASH-1400 (1975), "Reactor Safety Study," NUREG-75/014, National Technical Information Service, Springfield, VA.

Watson, I. A. (1982), "The Rare Event Dilemma and Common Cause Failures," Proceedings of the Annual Reliability and Maintainability Symposium, IEEE, New York.

Williams, D. W. (1972), "Common Mode Failures in US Commercial Power Reactors," master's thesis, University of Tennessee, Knoxville, TN.

Williams, R. V. et al. (1981), "Full Scale Nuclear Power Plant Availability and Safety Models," EPRI Research Project 1842-1 (draft), Electric Power Research Institute, Palo Alto, CA.

Wilson, J. R. and Crump, R. J. (1975), "Computer-Aided Common-Cause Analysis of an LMFBR System," Trans. Amer. Nucl. Soc., 22, pp. 474-475.

Worrell, R. B. and Burdick, G. R. (1976), "Qualitative Analysis in Reliability and Safety Studies," IEEE Trans. Reliab. R-25, pp. 164ff.

Worrell, R. B. and Stack, D. W. (1977), "Common-Cause Analysis Using SETS," SAND 77-1832, Sandia National Laboratories, Albuquerque, NM.

Worrell, R. B. and Stack, D. W. (1978), "A SETS User's Manual for the Fault Tree Analyst," SAND 77-1051, Sandia National Laboratories, Albuquerque, NM.

Worrell, R. B. and Stack, D. W. (1980), "A Boolean Approach to Common Cause Analysis," Proceedings of the Annual Reliability and Maintainability Symposium, IEEE, New York, pp. 363-366.

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BIBLIOGRAPHIC DATA SHEET

1 REPORT NUMBER (Assigned by TIDC, add Vol. No., if any)
NUREG/CR-4314
LA-10474-MS

2 Leave blank

3 TITLE AND SUBTITLE
A Brief Survey and Comparison of Common Cause Failure Analysis

4 RECIPIENT'S ACCESSION NUMBER

5 DATE REPORT COMPLETED

MONTH	YEAR
June	1985

6 AUTHOR(S)
Ray A. Waller

7 DATE REPORT ISSUED

MONTH	YEAR
June	1985

9 PROJECT/TASK/WORK UNIT NUMBER

8 PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Los Alamos National Laboratory
Los Alamos, NM 87545

10 FIN NUMBER
A7225-5

11 SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Division of Risk Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

12a TYPE OF REPORT
Informal

12b PERIOD COVERED (Inclusive dates)

13 SUPPLEMENTARY NOTES

14 ABSTRACT (200 words or less)

This paper presents a brief survey of methods and a list of references for analyzing common cause (mode) failures. Implicit models, explicit modeling techniques, and computer aids are included in the discussion. It is suggested that although current trends are emphasizing development of explicit models, a realistic assessment of data availability will force continued use of implicit or hybrid models in the immediate future.

15a KEY WORDS AND DOCUMENT ANALYSIS

15b DESCRIPTORS

16 AVAILABILITY STATEMENT

17 SECURITY CLASSIFICATION (This report)
Unclassified

18 NUMBER OF PAGES

19 SECURITY CLASSIFICATION (This page)
Unclassified

20 PRICE
$

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