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COMMON CAUSE ANALYSIS:
A REVIEW AND EXTENSION OF EXISTING METHODS

by

C. Heising, N. Rasmussen and C. Mak

Energy Laboratory Report No. MIT-El 82-038

October 1982

COMMON CAUSE ANALYSIS: A REVIEW AND EXTENSION OF EXISTING METHODS

by

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Foreword

This report details the methods developed and applied for performing common cause analysis at the systems and component level for large, highly redundant engineered safety systems in nuclear reactors. More generally, the methodology is also applicable to many other engineered systems outside of the nuclear area.

Major progress in this project was made in testing and refining the MOCUS-BACFIRE-II-BETAFACTOR analysis code, called MOBB, which takes the system fault tree diagram, generates cutsets and then employs the generic cause method developed by Fussell to identify common cause candidates. Then, the Beta-Factor method developed by Fleming is applied at the single component level to quantify the contribution to total system unavailability of common cause failures. Finally, an uncertainty analysis is performed to generate confidence bounds on both the top event and all cutsets employing both a standard Monte Carlo approach and improved Method-of-Moments method.

In addition, a second code was developed to apply the analysis approach of seismic risk analysis using discrete probability distribution (DPD) arithmetic. This code was applied to analyze a sample problem fault tree to include failures due to seismic events. This code is available for any follow-up work which should continue to apply the concept of seismic fragility more generally to the component (or system) susceptibility to various common cause events (e.g., corrosion, humidity, temperature , pressure , etc.).

This project completes the final version of the fault tree common cause analysis package, MOBB. Examples of application are included.

Special thanks are extended to Dr. Mohammed Modarres, formerly of SAI and now with the University of Maryland, for his advice, and to Dr. Karl Fleming of Pickard, Lowe & Garrick, Inc., for his help.

Carolyn D. Heising
Principal Investigator
September 30, 1982

Abstract

The quantitative common cause analysis code, MOBB, is extended to include uncertainties arising from modelling uncertainties and data uncertainties. Two methods, Monte Carlo simulation and the Method-of-Moments are used to propagate uncertainties through the analysis. The two different capabilities of the code are then compared. When component failure rates are assumed lognormally distributed, bounded lognormal (S_b) distributions are used to evaluate higher moment terms, as required by the Method-of-Moments, in order to minimize the effect of the tail of the lognormal. A code using the discrete probability distribution (DPD) method is developed for analyzing system unavailability due to common initiating events (internal and external). Sample problems demonstrating each approach are also presented.

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I. Introduction

As stated in the proposal, the purpose of this research project was to further assess and extend the MOCUS-BACFIRE computer code, first combined by Modarres in 1979(1) to provide the utilities with an effective and powerful tool for analysis and evaluation of common cause failures(CCF) in a system represented by its fault tree diagram.

The project has accomplished the following tasks:

(1) Assessment and comparison of MOCUS-BACFIRE, BACFIRE-II and COMCAN-II codes;

(2) redefining existing criteria for identifying CCFs and incorporating them into the selected code;

(3) selection and incorporation of a more sophisticated common cause quantification method; and

(4) evaluating sample problems chosen by the utility sponsors.

A detailed review of each of the specific contract tasks is presented in the attached Tables I- V.

The expected benefits of this work to the utilities are to obtain codes which are:

(1) capable of identifying common cause failures directly from the fault tree diagram;

(2) inexpensive and easy to operate;

(3) capable of automatically generating common cause candidates which are significantly contributing to the failure of the system due to common cause failures;

(4) capable of calculating the top event probability (or unavailability) by considering both random and common cause failures;

(5) especially suited for man-machine communication and its advantages.

TABLE I

REVIEW OF PROJECT TASKS

Task 1:	Assessment of existing qualitative common cause failure analysis codes that use generic cause approach to identify common cause candidates from minimal cutsets -COMCAN versions -BACFIRE versions -Sets (Sandia)
Status:	Completed April, 1981
Conclusion:	BACFIRE is preferable over the others, and is the code selected for integration with quantitative evaluation methods.

TABLE II

Task 2:	Choose an appropriate quantitative method to quantify the common cause candidates and evaluate the system unavailability.
Status:	Completed May, 1981
Conclusion:	Beta-factor method developed by Karl Fleming at General Atomic for HTGR-PRA is perferable. This method was integrated into the modified BACFIRE package. (It has also been refined and updated).
Product:	MOBB code. (MOcus - Bacfire - Beta factor method)

TABLE III

Task 3:	Implementation of the qualitative method chosen to quantify common cause candidates and evaluate system unavailability.
Status:	Completed August, 1981
Conclusions:	Sample problems were run using the MOBB code. These included analyses of the following two systems: -Auxiliary feedwater system (AFWS) -Fire protection system (FPS)
Documentation:	-Cho Mak's SM thesis -Paper for Portchester PRA meeting
Product:	Useful examples to guide utility efforts in systems analysis.

TABLE IV

Task 4:	Review and further extend the capabilities of the code to include uncertainty analysis, data collection and interpretation, redefine parameters and failure criterion.
Status:	Completed. Additionally, a separate code for uncertainty analysis using the DPD method of seismic risk analysis (HADES code). Examples have been run.
Preliminary Conclusions:	-Monte Carlo Method applicable -Has been incorporated into MOBB. -Sample problems run.

Further work needed (beyond this project scope);

-More efficient method required to reduce computer time.

TABLE V

Task 5:	Use of final version of the code for a detailed common cause failure analysis.
Status:	Completed.
Date of Completion:	End of September, 1982.
Final Product:	Revised code on tape for use in IBM-370 system.
Documentation:	-Project final report -Technical paper to be submitted to Reliability Engineering Journal

II. Quantitative Common Cause Failure Analysis

A. Dependent Failure Analysis

Dependent failures are an extremely important aspect of risk quantification and must be given adequate treatment to avoid gross underestimation of risk. Risk estimates can be many orders of magnitude off if the possibilities for dependent failures are overlooked. An example of how crucial common cause dependencies can be was the case of the Titanic; it was thought to be "unsinkable" because it was designed to have so-called "independent" compartments in the bottom hull of the ship. The Titanic sunk because the dependency between compartments was overlooked by the ship designers. This is an important lesson to all reliability engineers.

There are two major types of dependencies between events:

1. Actual physical dependencies between systems and/or events (e.g., seismic event and containment failure events.) These dependencies are discussed in Section 3.7, "Analysis of Dependent Failures," PRA Procedures Guide, NRC, 1982, K.N. Fleming, author. (1)
2. "State-of-knowledge" dependencies for nominally identical components whose failure rates are presumed identical. This type of data-related dependency is discussed further in Section 16.5, PLG Handbook, p. 109 on.(2)

The first kind of dependency is what is most often studied in common cause analysis. The second kind is somewhat new in the sense that it has only recently been identified. It is related

to the subjectivist (or Bayesian) theory of probability.

Mathematically, two failure events A and B are said to be dependent if their frequency, ϕ, satisfies:

$$\phi(A \text{ and } B) = \phi(A) \cdot \phi(B|A) \neq \phi(A) \cdot \phi(B) \qquad (1)$$

In other words, the frequency of concurrent failure events A and B (ϕ(A and B)) cannot be expressed simply as a product of the unconditional failure event frequencies $\phi(A)$ and $\phi(B)$. Dependent failures are defined into different groups as shown in Table VI(1) with methods which have been used to handle each shown in Table VII.

Analysis of Intercomponent Dependencies

The type of common cause failures that are of most interest here are those classified as Type 3 in Table VI, or intercomponent dependencies. Before the quantification of the system unavailability can be completed, it is necessary to analyze the possibilities for dependencies among the basic component failures.

TABLE VI

DEPENDENT FAILURE CLASSIFICATIONS (1)

Type 1	Common Cause Initiators (external events) These include external and internal events that have the potential for initiating a plant transient and increase the probability of failure in multiple plant systems. These events usually, but not always, result in severe environmental stresses on components and structures. Examples include fires, floods and earthquakes.
Type 2	Intersystem Dependencies These are events or failure causes that create interdependencies among the probabilities of failure of multiple systems. States another way, intersystem dependencies cause the conditional probability of failure of a given system along an accident sequence to be dependent on the success or failure of systems that precede it in the sequence. There are several subtypes of interest in risk analysis.
Type 2A	Functional Dependencies These are dependencies among systems that follow from the plant design philosophy, system capabilities and limitations, and design base. One example is a system that is not used or needed unless other systems have failed. Another is a system that is designed to function only in conjunction with the successful operation of other system.
Type 2B	Shared Equipment Dependencies These are dependencies of multiple systems on the same components, subsystems, or auxiliary equipment. Example are: 1) a collection of pumps and valves that provide a coolant injection and a coolant recirculation function when the functions appear as different events in the event tree, and 2) components in different systems fed from the same electrical bus.

TABLE VI, cont'd (1)

Type 2C Physical Interactions These are fialure mechanisms, similar to those in common cause initiators, that do not cause an initiating event but nonetheless increase the probability of multiple system failures occurring at the same time. Often they are associated with extremeenvironmental stresses created by the failure of one or more systems after an initiating event. For example, the failure of a set of sensors in one system can be caused by the excessive temperature resulting from the failure of a second system intended to cool the heat source.

Type 2D Human Interaction Dependencies These are dependcies introduced by human actions, including errors of omission and commission. The persons involved can be anyone associated with a plant life cycle activity, including designers, manufacturers, constructors, inspectors, operators, and maintenance personnel. Such a failure occurs, for example, when an operator turns off a system after failing to correctly diagnose the plant condition.

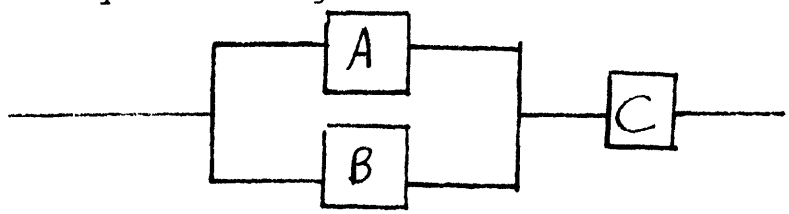
Type 3 Intercomponent Dependencies These are events or failure causes that result in a dependence among the probabilities of failure of multiple components or subsystems. The multiple failures of interest in risk analysis are usually within the same system or the same minimal cutset that has been identified for a system or an entire accident sequence. Subtypes 3A, 3B, 3C and 3D are defined to correspond with subtypes 2A, 2B, 2C and 2D, respectively, except that the multiple failures occur at the subsystem and component level instead of at the system level.

TABLE VII

METHODS FOR MODELLING DEPENDENT FAILURES (1)

Dependent Failure Type	Recommended Method of Modelling
Type 1: Common Cause Initiators	1-a Event Specific Models 3-a Qualitative Search Procedures
Type 2A: Intersystem Functional Dependencies	1-b Event Tree/Boundary Condition Method
Type 2B: Intersystem Shared Equipment Dependencies	1-b Event Tree/Boundary Condition Method 1-c Fault Tree Linking Method
Type 2C: Intersystem Physical Interactions	1-a Event Specific Models 3-a Qualitative Search Procedures
Type 2D: Intersystem Human Interactions	1-b Event Tree/Boundary Condition Method 1-c Fault Tree Linking Method 1-d Fault Tree Cause Analysis 1-e Human Reliability Model
Type 3: Intercomponent Dependencies	1-d Fault Tree Cause Analysis 2-a Beta Factor Method 2-b Binomial Failure Rate Model

Consider a system of three components A, B, and C; let the reliability block diagram be:



The corresponding system unavailability, Q, is:

$$Q = P(A \text{ and } B) + P(C) - P(A \cap B \cap C)$$

$$= P(A) \cdot P(B|A)[1-P(C|A \cap B)] + P(C)$$

where

$P(x)$ = availability of component x

$P(y|z \text{ and } t)$ = unavailability of component y given components Z and t are failed; $P(B|A) >> P(B)$ in this example.

There are three basic approaches to CCFA:

(1) Develop causes explicitly in fault trees or cause tables (primarily qualitative approach)

(2) Beta-Factor Method (Parametric)

(3) Binomial Failure Rate Model (Parametric)

The greatest limitation of approach (1) is that in an effort to ensure completeness, an intractable number of dependencies are identified. Taken separately, these dependencies can often be discounted on the basis of a perceived low occurrence probability. Experience shows, however, that as a class they cannot be dismissed. Thus it is difficult to know which common cause candidates are important and which are not. Therefore, we must go to quantitative procedure, as is done in this project, such as the Beta-Factor method. Before doing this, however, we review some previous work in this area.

B. Previous Work on Quantification of Common Cause

Unavailability calculations of engineering safety features and risk assessment studies (3,4) revealed the importance of considering potential common cause failures in estimating the probability of failure of redundant systems. It is a well-recognized fact that reliability predictions of redundant systems are overestimated when the potential for common cause failures is not properly accounted for. In fact, the RSS amply demonstrated that CCF may contribute the most to system unavailability.

The state-of-the-art of CCF analysis up to 1979 has been reviewed by Rasmussen et al. (5). Hayden (6) separated CCF's into component and system failures and categorized them in terms of generic failure mechanisms such as design error, human error and generic events. Apostolakis (7) used a constant hazard rate for reliability and redefined the hazard rate by using a point estimate of the conditional probability that a unit failure is due to a common cause failure.

Certainly the most thorough CCF analysis was performed as part of the RSS in each of the following analysis steps:

- Event tree construction
- Fault tree construction
- Fault tree quantification
- Event tree quantification
- Special engineering investigations

Computerized efforts in the qualitative and quantitative procedure of common cause failures were begun with special emphasis after the publication of the RSS. Burdick et al,(8) reported on the COMCAN

code. This code is designed to aid in the qualitative determination of:

(1) single secondary events that could fail an entire minimum cutset, given all components in the cutset share the same susceptibility location.

(2) Common links among components such as common circuitry, common maintenance personnel or common manufacturers for all components in a cutset.

As a result, COMCAN requires as one of its inputs a set of minimal cutsets which have been obtained by some other qualitative analysis code. It is quite apparent that for large fault trees with a high degree of replication and the possibility of several common cause failures, the computational efforts involved in the minimal cutset sorting become tremendous, if not impossible, due to the large amount of minimal cutsets. Modarres et al. (1) have developed a computer code package to resolve this difficulty by coupling the cutset generator code MOCUS (9) and common cause failure analysis code BACFIRE (10) to obtain the MOCUS-BACFIRE Package. The BACFIRE Code is a newer and more adequate version of the COMCAN Code. However, a newly developed version of the COMCAN Code, which is called COMCAN-II (11), has been recently developed to directly evaluate common cause failures from the fault tree diagram. Similarly, BACFIRE was extended to obtain the BACFIRE-II code (12). Therefore, the codes COMCAN-II, BACFIRE-II and MOCUS-BACFIRE have relatively similar capabilities. However, they employ different algorithms to determine CCFs, and the efficiency and limitations of

these codes had not been compared and assessed yet.* The development of the COMCAN methodology laid the ground for the first time with basic rules which will be common to all future efforts involving common cause handling. The most important thing which was realized during the course of the development of this code is the recognition of the importance of generic classification. The possible physical sources for a specific secondary event can develop into an absolutely endless list. Only a unique generic classification makes the search for minimal cutset sharing susceptibilities a tractable task. For this purpose, a preprocessor has been implemented in COMCAN which needs as input generic categorization of secondary causes.

A special category has been added which links conditions among components to locate potential common cause failures of minimal cutsets. The other three categories considered by COMCAN are:

- Mechanical or Thermal
- Electrical or Radiation
- Chemical or Miscellaneous

Recent studies (13, 14) have shown that the criteria for identifying a cutset as a common cause candidate in the COMCAN code is not unique and sufficient for a complete CCF analysis. It is important, however, to select an adequate set of CCF criteria in order to obtain a set of adequate common cause candidates.

The review of computerized qualitative common cause failure analysis suggests the following conclusions. First, the original COMCAN code approach, which uses the complete minimal cutset information, has no potential for further development because of

*They have been compared in this project.

a prohibitive amount of cutsets that must be input to the code for a large fault tree. Second, the codes MOCUS-BACFIRE and COMCAN-II eliminate the necessity to input the cutsets. Therefore, instead of the cutsets, they require the fault tree to be input. However, they had not been fully tested and assessed.* A careful revision is required to establish a set of new criteria for identification of common cause candidates from the cutsets.

The state-of-the-art in common cause quantification is largely determined by the work described in WASH-1400 and the new developments by Vesely (15). Whereas in WASH-1400 common cause failure probabilities were evaluated using upper and lower probability bounds, Vesely showed that common cause failure probabilities can also be evaluated directly by using the multivariate exponential model developed by Marshal and Olkin (16). For this purpose, Vesely developed a statistical estimation technique for cases where common cause failures are repairable. Two special cases were examined, the constant failure rate case and the binomial failure rate case. A BWR scram system served as an example. In another paper, Johnson and Vesely (17) applied the same technique to the common cause analysis of valve leakages. In both papers, actual data were used from EPRI records and Licensee Event Reports (LER), respectively. It should be noticed that the quantification model used is dependent upon the data population and presupposes that the components from a given defined population are subject to similar failure causes.

Fleming and Raabe (18) compared GA's approach (known as β-method) to both aforementioned methods (i.e., RSS and Vesely's methods).

---

*They have been so compared and assessed in this project.

The objective of their paper was to show the validity of the common cause coupling β-method as compared to the bounding technique of the RSS and the multivariate exponential distribution of Vesely. Modarres et al. (1) have recently studied a method to quantify CCF affect by using a Markovian approach. They used exponential distributions to model and evaluate the failure probability of cutsets due to both random cause and common cause failures. A simplified aux-feed system served as an example, and failure probabilities were close to that predicted by the RSS bounding method.

C. The Beta-Factor Method (18)

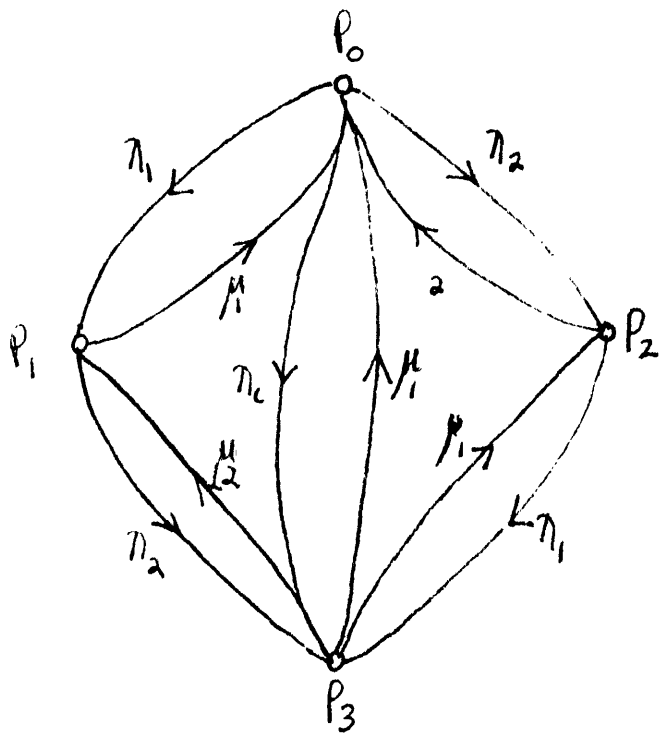
Definition of the Beta Factor

The Beta-Factor of a component event is defined as the fraction of all common cause failures to the total number of failures, which include both independent and common cause failures. Since most components are susceptible to more than one common cause, the level of susceptibility is used to specify the relative occurrences of a secondary failure of a component.

The common cause candidates identified can be considered as a subsystem. To quantify the common cause candidates, Markov models are applied to these subsystems. The failure and repair rates are assumed to be exponentially distributed. A non-identical repairable two-component system with common cause failure is used as an example. The Markov state transition diagram is shown in Figure 1. The following assumptions are made to develop the model:

Figure 1

State Transition Diagram for Repairable 2-Component System



$P_0(t)$ = probability at time t, both units are operational

$P_1(t)$ = probability at time t, only unit i has failed, for i = 1,2

$P_3(t)$ = probability at time t, both units have failed

λ_1 = independent failure rate of unit i, for i = 1,2

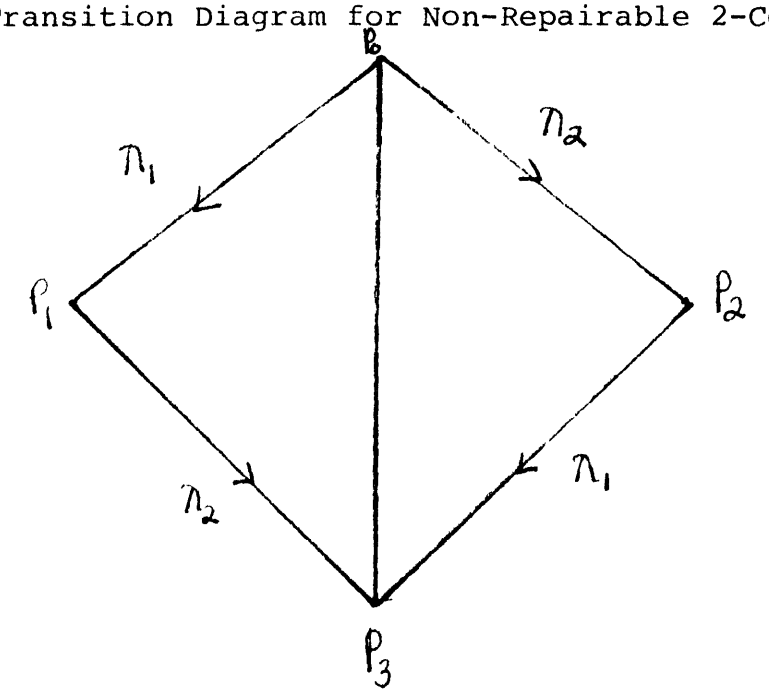
λ_c = common cause failure rate

μ = repair rate of unit i, for i = 1,2

μ_3 = repair rate of both units, 1 and 2

Figure 2

State Transition Diagram for Non-Repairable 2-Component System



(1) Common cause and independent failures are statistically independent,

(2) common cause failures can only occur with more than one unit, and they fail simultaneously.

The system of first order differential equations can be written for the model as:

$$P_0'(t) = -\left(\sum_{i=1}^{2}\lambda_i(t)+\lambda_c(t)\right)P_0(t)+\sum_{i=1}^{3}P_i(t)\mu_i(t) \qquad (1)$$

$$P_1'(t) = -(\lambda_2(t)+\mu_1(t))P_1(t)+P_3(t)\mu_2(t)+P_0(t)\lambda_1(t) \qquad (2)$$

$$P_2'(t) = -(\lambda_1(t)+\mu_2(t))P_2(t)+P_0(t)\lambda_2(t)+P_3(t)\mu_2(t) \qquad (3)$$

$$P_3'(t) = -\left(\sum_{i=1}^{2}\mu_i(t)+\mu_3(t)\right)P_3(t)+\sum_{i=1}^{2}P_i(t)\mu_{(3-i)}(t)+P_0(t)\lambda_c(t) \qquad (4)$$

$$\sum_{i=1}^{3}P_i(t) = 1 \qquad (5)$$

If all the failure and repair rates are time independent and a set of appropriate boundary conditions are given, equations (1) to (5) are then a set of linear differential equations which can be solved by using Laplace transform techniques. The system unavailability at time t is $P_3(t)$ for a 2-component system in parallel.*

Beta-Factor Method

The total failure rate for each unit, λ, is assumed constant with time and can be expanded for its independent and common cause components:

$$\lambda = \lambda_i + \lambda_c \qquad (6)$$

where λ_i is the unit failure rate for independent causes, and

λ_c is the unit failure rate for common cause.

*Unavailability expressions including test and repair have recently been developed by Heising and Fleming in a paper soon to be published.

The component parameter Beta is defined as the fraction of the total failure rate attributable to common cause failures:

$$\beta = \lambda_c/\lambda \tag{7}$$

For the same Markov model presented in the previous section, if the following assumptions are made, then the system model can be simplified as shown in Figure 2:

(1) constant failure rates with time t,

(2) consider non-repairable components only, and

(3) at time t=0, both units are operable,

i.e. $P_0(t=0)=1$ and $P_i(t=0)=0$, for i=1,2,3.

The system of differential equations for the model is:

$$P_0'(t) = -(\lambda_1+\lambda_2+\lambda_c)P_0(t) \tag{8}$$

$$P_1'(t) = -(\lambda_2+\beta_2\lambda_2)P_1(t)+\lambda_1 P_0(t) \tag{9}$$

$$P_2'(t) = -(\lambda_1+\beta_1\lambda_1)P_2(t)+\lambda_2 P_0(t) \tag{10}$$

$$P_3'(t) = \lambda_c P_0(t)+(\lambda_2+\beta_2\lambda_2)P_1(t)+(\lambda_1+\beta_1\lambda_1)P_2(t) \tag{11}$$

The system unavailability at time to the second order is:

$$F(t) = P_3(t)=\lambda_c t + \lambda_1\lambda_1 t^2 + \lambda_1\lambda_1(\beta_1+\beta_2)\frac{t^{2}}{2} - \ldots \tag{12}$$

= Pr(common cause failure) and Pr(random failures) + Pr(partial common cause failures) + truncation errors

Generalized to a non-identical and non-repairable n-component system:

$$F(t) = \lambda_c t + \sum_{i=1}^{n}\lambda_i t^n + \sum_{j=1}^{n}\lambda_j t \sum_{\substack{i=1\\ i\neq j}}^{n}\beta_i\lambda_i t^{(n-1)} + \ldots \tag{13}$$

<u>Data Parameters for Beta-Factor Method</u>

The major advantage of using the Beta-Factor method to quantify

common cause candidates is that the model parameters are readily available from existing data bases. Consider an operating time period, T, during which data have been collected from each of the N systems where each system consists of two components of the same type:

$$\lambda = \frac{1}{2NT} \sum_{i=1}^{N} (n_{i1}+n_{i2}+2n_{ic}) \tag{14}$$

$$\lambda = \frac{1}{2NT} \sum_{i=1}^{N} 2n_{ic} \tag{15}$$

$$\beta = 2 \sum_{i=1}^{N} n_{ic} / \sum_{i=1}^{N} (n_{i1}+n_{i2}+2n_{ic}) \tag{16}$$

where n_{i1} = number of random failure of component 1 in system i,

n_{i2} = number of random failure of component 2 in system i, and

n_{ic} = number of common cause failure.

Estimations of the Beta Factor for different component types obtained from reliability experience data are found to have values very closely clustered in the range from 0.1 to 0.2 [11,12]. Therefore, component types with unknown Betas can be easily approximated. For minimal cutsets with more than two units, the Beta Factor model assumes that all units fail if a common cause failure occurs. The method is most useful for analyzing common cause failures in systems with limited redundancy, two or three units. The value λ_c for a minimal cutset with different components cannot be estimated from data directly due to the large number of different combinations of component types. However, cross-component dependencies can generally be neglected.

When individual failure probabilities of each cutset are calculated, the system failure probability (unavailability) can be calculated as a function of the failure probabilities of different cutsets, C_i:

$$F(S) = \sum_i Pr(C_i) - \sum_{i \neq j} Pr(C_i \Omega C_j) + \ldots + (-1)^{m-1} Pr(C_1 \Omega C_2 \ldots \Omega C_m) \quad (17)$$

III. The MOBB Code

A. Code Description

The MOBB code consists of the package MOCUS, BACFIRE-II and a project coded Beta-Factor method for quantifying both cutset and top event unavailabilities and uncertainty about the point values calculated. This code is described in detail in the MOBB code User's Manual (10). The basic flow diagram of the MOBB code is shown in Figure 3. The input to the code consists of the system logic model (fault tree), common cause types and physical domains, specification of individual component mean-value failure rates (either on demand or per hour), Beta-Factors, component susceptibilities and rankings as supplied by the manufacturer or as determined through direct user experience. The output is a listing of the common cause candidates, both for relative unavailability and as a function of the specific generic cause (see Table VIII). The total system unavailability is also calculated. The uncertainty bounds are also provided, in that mean and median values are printed out, as well as with error factors so that 5% and 95% confidence bounds can be determined, both at the top event and individual cutset level. (The uncertainty analysis capability of MOBB is discussed further in III.C of this report.)

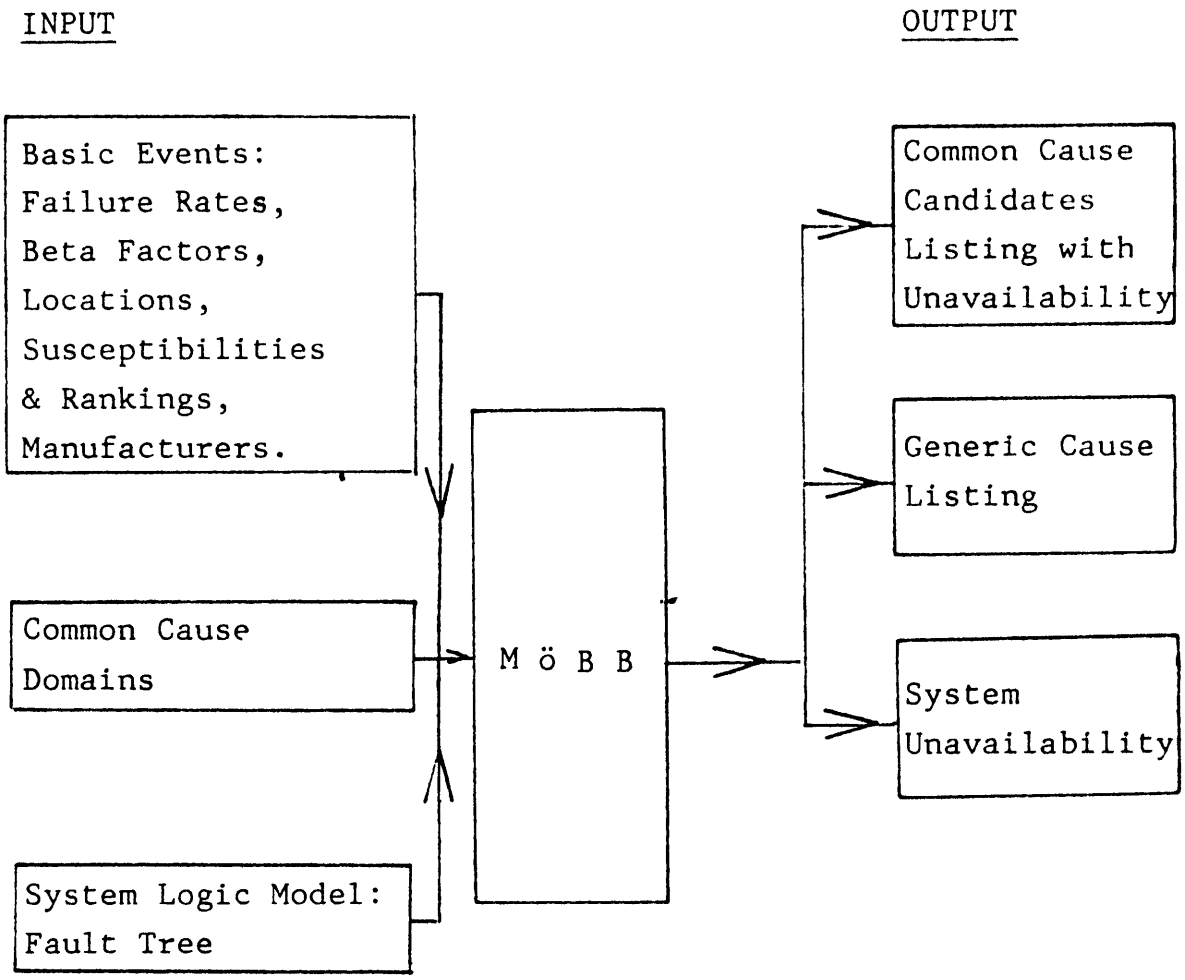


Figure 3

Flow Diagram of MOBB Code

TABLE VIII

GENERIC CAUSES OF ENVIRONMENTAL STRESS (SECONDARY FAILURES)

* MECHANICAL AND THERMAL GENERIC CAUSES

GENERIC CAUSE	EXAMPLE SOURCES
IMPACT	PIPE WHIP, WATER HAMMER
VIBRATION	MACHINERY IN MOTION
PRESSURE	EXPLOSION, OUT-OF-TOLERANCE
MOISTURE	CONDENSATION, PIPE RUPTURE

* ELECTRICAL OR RADIATION GENERIC CAUSES

ELECTROMAGNETIC INTERFERENCE	WELDING EQUIPMENT, ETC.
RADIATION DAMAGE	NEUTRON SOURCES
CONDUCTING MEDIUM	MOISTURE, CONDUCTIVE GASES
OUT-OF-TOLERANCE VOLTAGE	POWER SURGE
OUT-OF-TOLERANCE CURRENT	SHORT CIRCUIT, POWER SURGE

* CHEMICAL OR MISCELLANEOUS CAUSES

CORROSION	ACIDS
CORROSION	OXIDATION IN H_2O MEDIUM
OTHER CHEMICAL PROCESSES	GALVANIC CORROSION ,ETC.
CARBONIZATION	HC IN LIQUID SODIUM
BIOLOGICAL	POISONOUS GASES, ETC.

B. Sample Problems

Two problems are performed below demonstrating the use of the MOBB code. The first demonstrates the ability of MOBB to evaluate and quantify individual system cutsets, while the second demonstrates that not all problems will require the full application of code capabilities (i.e.: in the second problem, one common cause type dominates--human error). These examples demonstrate that utility system common cause analysis must still depend largely on the analyst's interpretation and understanding of the problem--no code can substitute for this basic requirement.

B.1. Warehouse Fire Protection System (FPS)

To demonstrate the use of the MOBB code, a sample problem has been devised based on a system for fire protection installed at a fictitious warehouse. (A similar system is used as an example in Part IV.C of this report, the difference being that on- and off-site electric power is included in that example.) The schematic flow diagram for the fire protection system (FPS) is shown in Figure 4. In Figure 5, the system fault tree is drawn.

In Figure 6, a sample floor map and suceptibility map is shown, whereby the code user must specify the relative location of the components in his system and their geometrical susceptibility (i.e., across all compartments, only a few, or only one).

Then, the user must identify the particular failure mode of each component; in this case four modes are identified, as shown in Table IX. The susceptibility type must be specified for each domain, as shown in Table X, where "P" stands for generic cause or

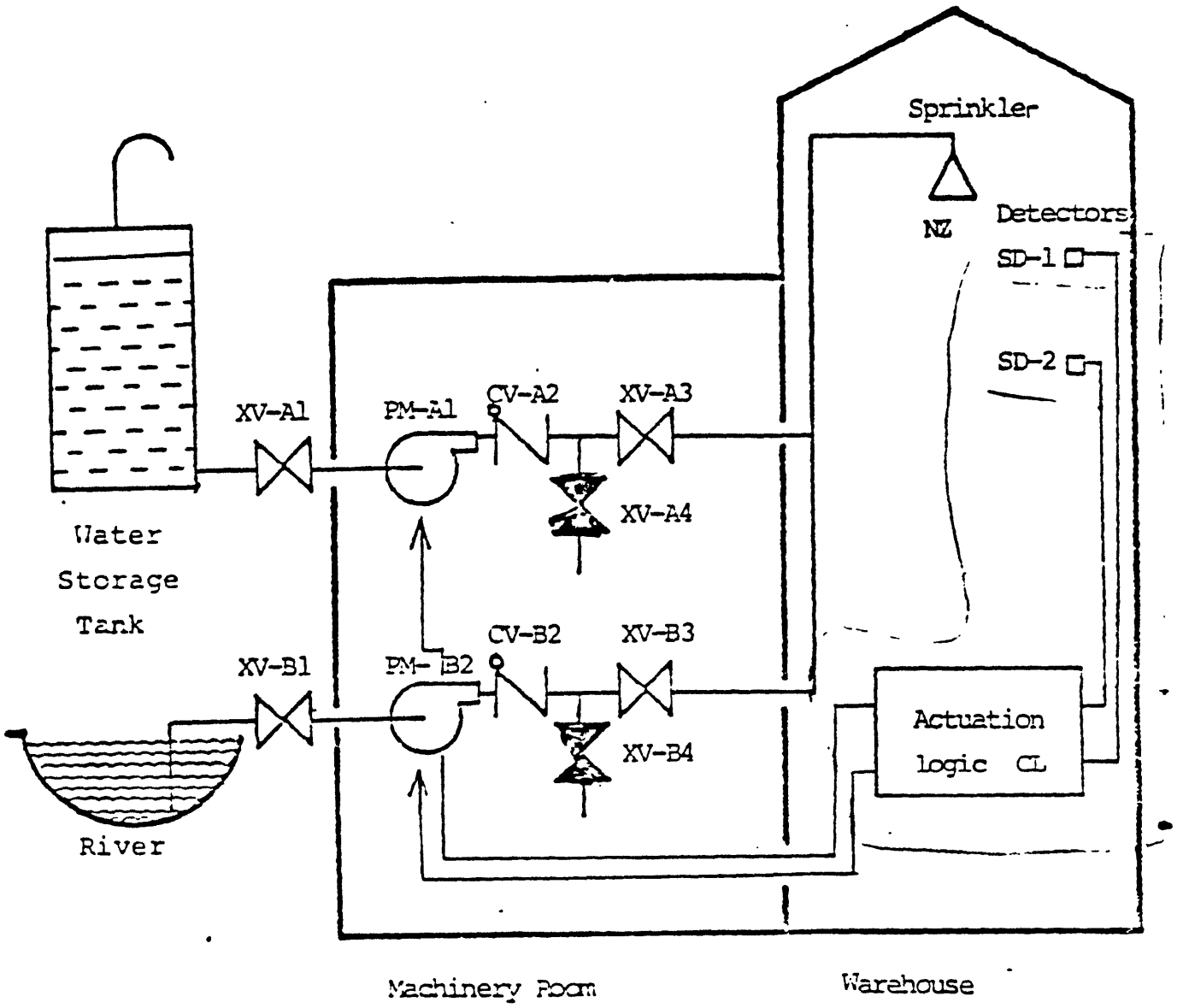


Figure 4: Schematic Flow Diagram of the FPS

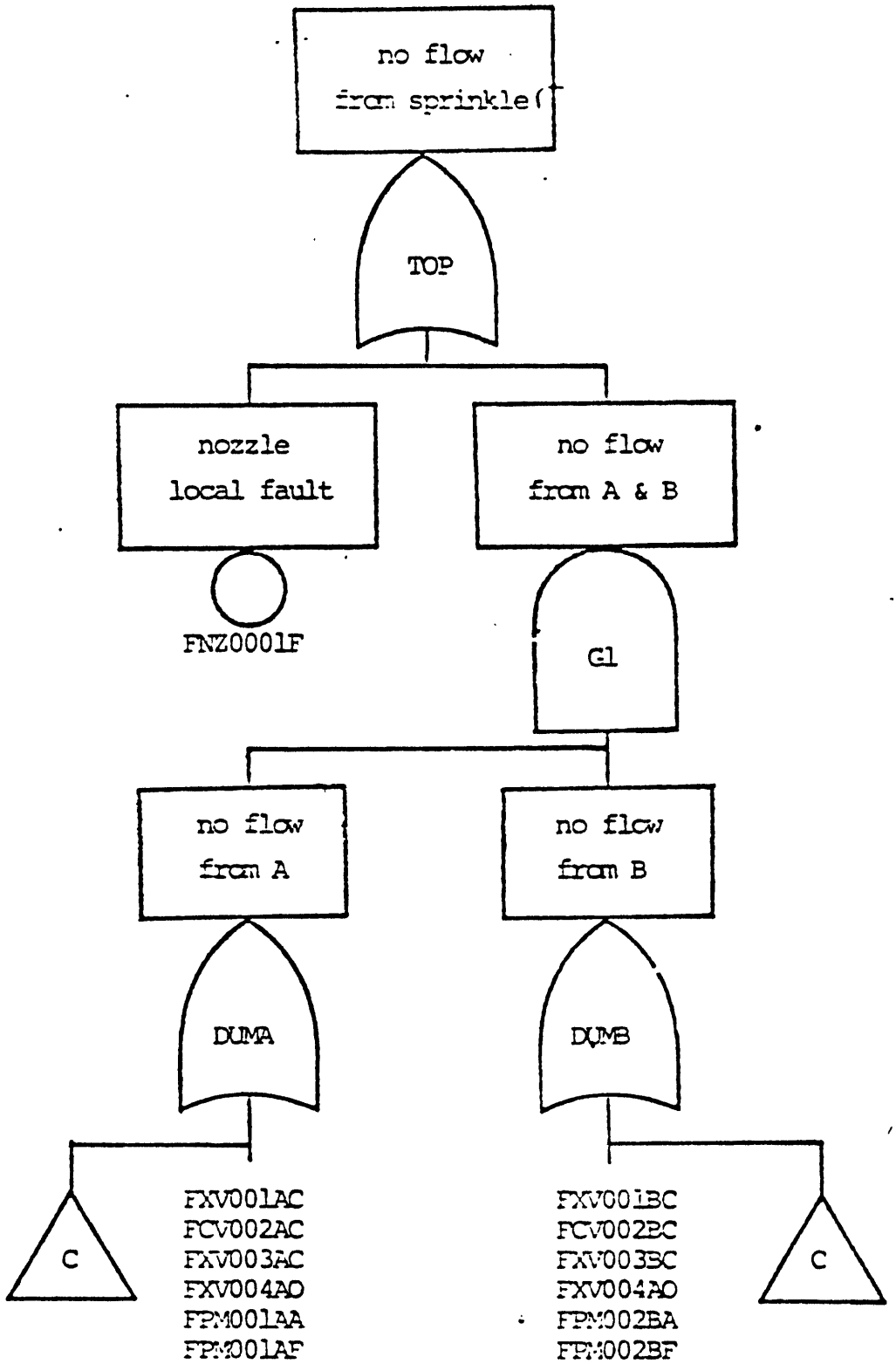


Figure 5: System Fault Tree

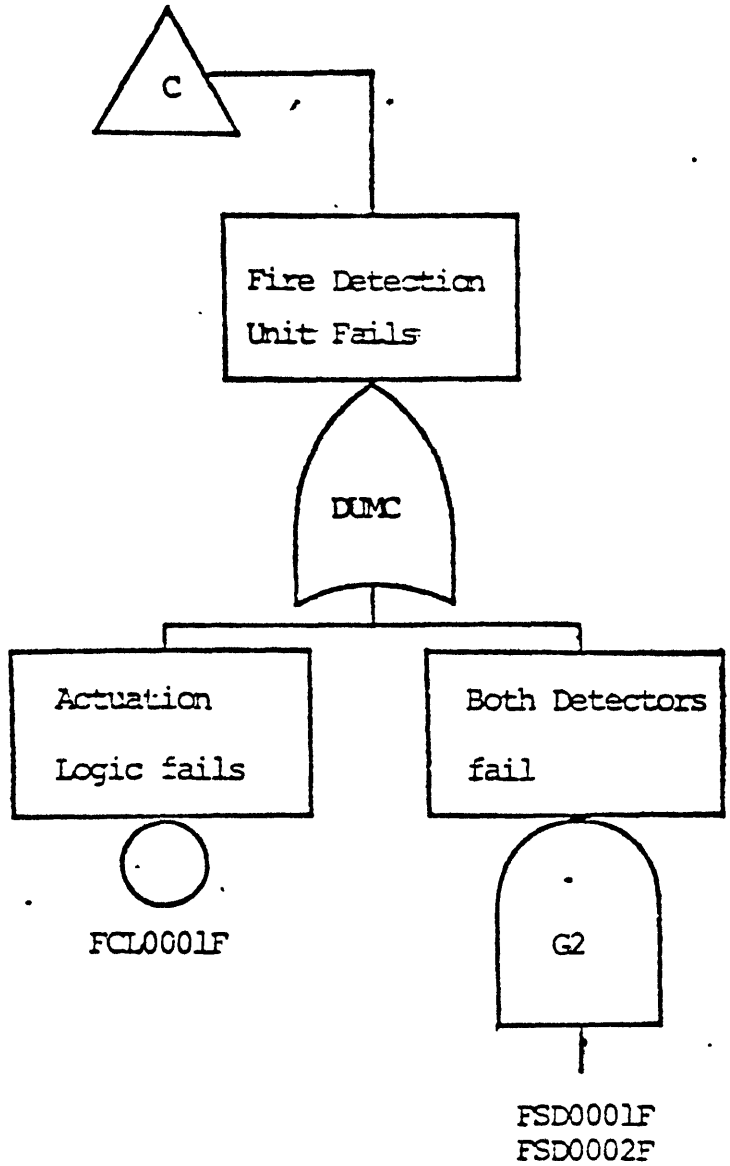


Figure 5 (continued): System Fault Tree

Figure 6: Floor Map and Susceptibility Maps

Floor Map

A1	A2	A3

MAP - A

1MPA

MAP - B

1MPB	2MPB

MAP - C

1MPC	2MPC	3MPC

Table IX : Failure Mode Code

Symbol	Failure Mode
C	Closed
O	Open
A	Fail to start
F	Fail to function

Table X : Susceptibility Domain

Susceptibility	Domain	Physical Location
P	1MPA	A1, A2, A3
I, V, T	1MPB	A1
	2MPB	A2, A3
G, M, C, O	1MPC	A1
	2MPC	A2
	3MPC	A3

susceptibility to pressure, "T" for temperature, "V" for vibration, etc. Then, each component in the system must be labelled for input into the code by type, number, and failure mode (Table XI). Finally, the common cause failure data and total component failure rates, either input on a per hour or per demand basis, must be defined, as shown in Table XII.

Results of running the MOBB code for this sample problem revealed thirty-four common cause candidates (See Tables XIII - XV; sample computer output) which include two cutsets with only one component. Strictly speaking, they cannot be defined as common cause candidates, but are included because they are significant contributors to the total system failure. The system failure probability due to independent failure is estimated at 1.21E-4 and the failure probability due to common cause failure is 4.12E-4 (i.e. system failure due to common cause is three times as high as failure due to random failures). The total system failure probability is 5.33E-4 compared to the original single pumping train system which has a failure probability of 3.4E-3. There is almost an order of magnitude improvement in decreasing system unavailability.

If the assumption of total statistical independence of components is valid, the system unavailability can be as low as 1.0E-5 (the single component cutsets are dominant contributors). On the other hand, if the failure is totally dependent, there will be no improvement by adding an additional train to the FPS. In practice, the result often attains some value between these two extremes.

Table XI: Component Code

Symbol	Component
FXV001A	Manual valve XV-A1
FXV001B	Manual valve XV-B1
FXV003A	Manual valve XV-A3
FXV003B	Manual valve XV-B3
FXV004A	Manual valve XV-A4
FXV004B	Manual valve XV-B4
FCV002A	Check valve CV-A2
FCV002B	Check valve CV-B2
FNZ0001	Sprinkle system (nozzle)
FPM001A	Electric driven pump PM-A1
FPM002B	Electric driven pump PM-B2
FCL0001	Actuation logic
FSD0001	Detector SD-1
FSD0002	Detector SD-2

Table XII: Common Cause Failure Data

Basic Event	Failure Rate	Beta Factor	Generic Cause Susceptibility	Special Condition
FXV001AC	1.0E-5/h	.23	V, O	M1, T1, I1
FXV001BC	1.0E-5/h	.23	V, O	M1, T1, I1
FXV003AC	1.0E-5/h	.23	V, O	M1, T1, I1
FXV003BC	1.0E-5/h	.23	V, O	M1, T1, I1
FXV004AO	1.0E-5/h	.23	V, O	M1, T1, I1
FXV004BO	1.0E-5/h	.23	V, O	M1, T1, I1
FCV002AC	1.0E-5/h	.23	V, P, O	M1, T1, I1
FCV002BC	1.0E-5/h	.23	V, P, O	M1, T1, I1
FPM001AA	1.0E-3/D	.14	P, O	E1, M2, T1, I1
FPM001AF	2.0E-4/h	.06	P, V, G, O	E1, M2, T1, I1
FPM002BA	1.0E-3/D	.14	P, O	E1, M2, T1, I1
FPM002BF	2.0E-4/h	.06	P, V, G, O	E1, M2, T1, I1
FNZ0001F	1.7E-6/h	.10	I, V, P, O	M1, T1, I1
FSD0001F	2.8E-4/D	.20	T, C, M, O	E2, M3, T2, C1
FSD0002F	2.8E-4/D	.20	T, C, M, O	E2, M3, T2, C1
FCL0001F	1.0E-5/D	.20	T, C, M, O	E2, M3, T2, C1

TABLE XIII

****
* QUALITATIVE FAILURE CHARACTERISTICS *
****

VIBRATION
DOMAIN= 1MPB

CANDIDATE NUMBER	FAILURE PROBABILITY
4	0.1846E-05

VIBRATION
DOMAIN= 2MPB

CANDIDATE NUMBER	FAILURE PROBABILITY
28	0.1020E-04
18	0.1846E-05
11	0.1710E-05
24	0.1448E-06
21	0.1448E-06
26	0.1448E-06
25	0.1448E-06
15	0.1448E-06
19	0.5929E-08
13	0.5929E-08
12	0.5929E-08
17	0.5929E-08

PRESSURE
DOMAIN= 1MPA

CANDIDATE NUMBER	FAILURE PROBABILITY
28	0.1353E-04
33	0.9490E-05
11	0.1710E-05
34	0.1617E-05

TABLE XIV

OUTPUT FROM MOBABE II

****
* COMMON CAUSE CANDIDATES *
****

CANDIDATE NUMBER		
1	BASIC EVENT: FNZ0001F	
	MINIMAL CUT SET WITH ONE BASIC EVENT	FAILURE PROBABILITY
		0.1700E-06
2	BASIC EVENT: FCL0001F	
	MINIMAL CUT SET WITH ONE BASIC EVENT	FAILURE PROBABILITY
		0.1000E-04

TABLE XV

11 BASIC EVENTS. FCV002AC FCV002BC

COMMON CONDITION -- FIRST CRITERION	FAILURE PROBABILITY
MAINTENANCE PROCEDURE 1	0.5969E-05
TESTING PROCEDURE 1	0.6021E-05
INSTALLATION 1	0.4265E-05
TRUE VALUE HARDWARE	

COMMON SUSCEPTIBILITY -- SECOND CRITERION	FAILURE PROBABILITY
VIBRATION	0.1710E-05
PRESSURE	0.1710E-05
OXIDATION (CORROSION)	0.2561E-05

12 BASIC EVENTS: FCV002AC FXV003BC

COMMON CONDITION -- FIRST CRITERION	FAILURE PROBABILITY
MAINTENANCE PROCEDURE 1	0.5929E-08
TESTING PROCEDURE 1	0.5929E-08
INSTALLATION. 1	0.5929E-08
TRUE VALUE HARDWARE	

COMMON SUSCEPTIBILITY -- SECOND CRITERION	FAILURE PROBABILITY
VIBRATION	0.5929E-08
OXIDATION (CORROSION)	0.5929E-08

B.2 Millstone-I Automatic Pressure Relief (APR) System

A sample problem was analyzed for dominant common cause contributors. The system analyzed was the Millstone-I APR (automatic pressure relief system). A description of the system and the fault tree for that system are given in Appendices C and D. It was found that human error dominates, so that the MOBB code was not fully applied to run this problem. Results are shown in Figures 7 and 8.

C. Propagation of Uncertainty in MOBB

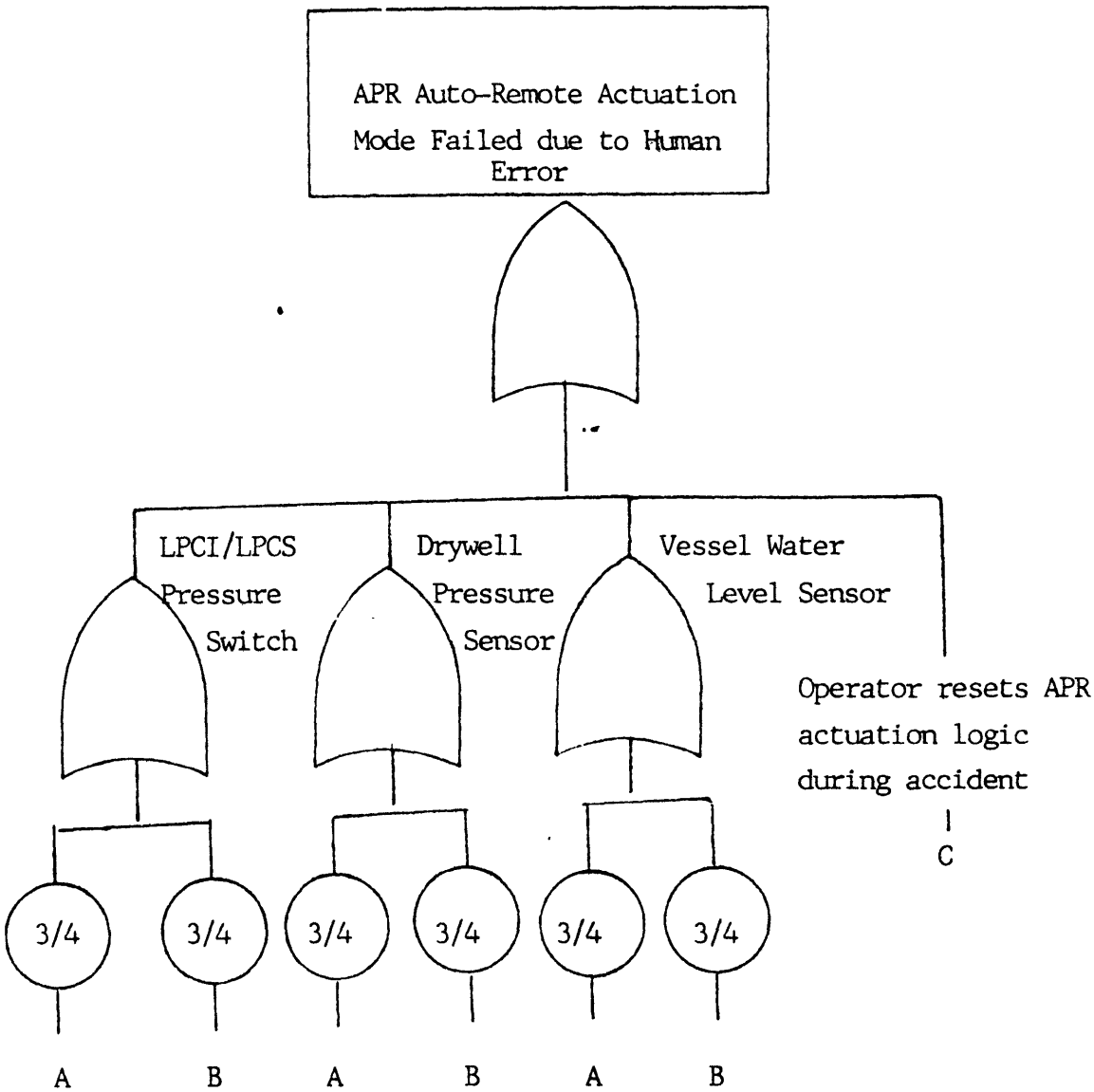
The MOBB code (20) was modified (as shown in Tables XVI-XVII) to compare the Monte Carlo simulation method for propagating component failure rate uncertainties through the fault tree as compared to the more analytic Method-of-Moments. This was done to establish a distribution on cutset availability rather than printing only a single point-value.

It was found that the Method-of-Moments was by far the more efficient of the two approaches. Improvements on the Method-of Moments were made by using modified lognormal distributions to model component failure rates. These are termed, "S", for the standard lognormal, "S_B" for the bounded lognormal, and "S_t" for the truncated lognormal. The mathematical formulae for each is given in Table XVIII, with behavior of the functions shown in Figure 9. The bounded lognormal, S_B, was found to render the best results on a sample problem taken from a recent reference,* where results agreed well with a Monte Carlo simulation of 3,000 trials (Table XIX). The Method-of-Moments was therefore implemented with the S_b approximation.

*Work done at Westinghouse.

Figure 7

Fault Tree for APR System for Human Error



A: not restored to service after test or maintenance

B: switch or sensor miscalibrated

Fault Tree for Human Error

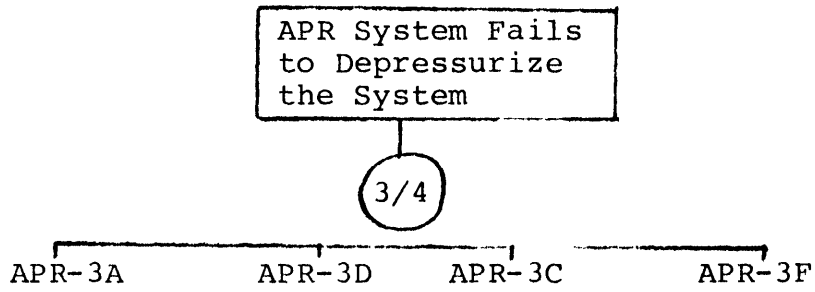
Figure 8

APR System Analysis

1) Blowdown for LPCI systems

Scenario: small LOCA

Success Criteria: 2 out of 4 Auto/Remote APR Valves actuate



2) Relief/Safety Valves Actuation

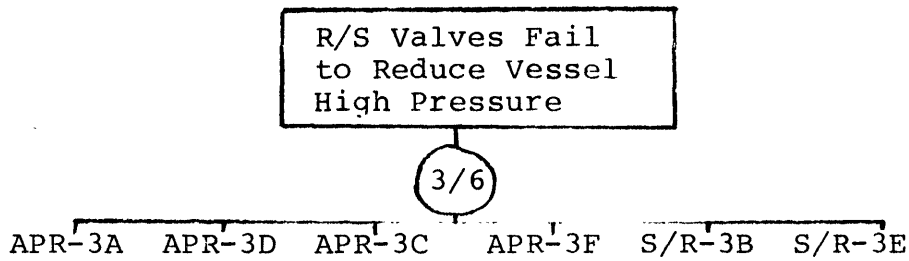
Function: to relieve high vessel pressure

Full Power Pressure: 1,000 psig

Design Limit Pressure: 1,375 psig

Success Criteria: Any 4 out of the 6 APR or R/S Valves

Scenario: -Turbine Trip from Full Power
-Failure of the Turbine Bypass System
-Failure of the Direct Reactor Scram based on Stop Valve Position



3) Manual Actuation Mode

All six valves can be remotely opened from the control room

Success criteria:	-Relief Pressure	4/6
	-Blowdown (auto/remote)	2/4
	-Blowdown (manual)	2/6

TABLE XVI

MOBB WITH MONTE CARLO

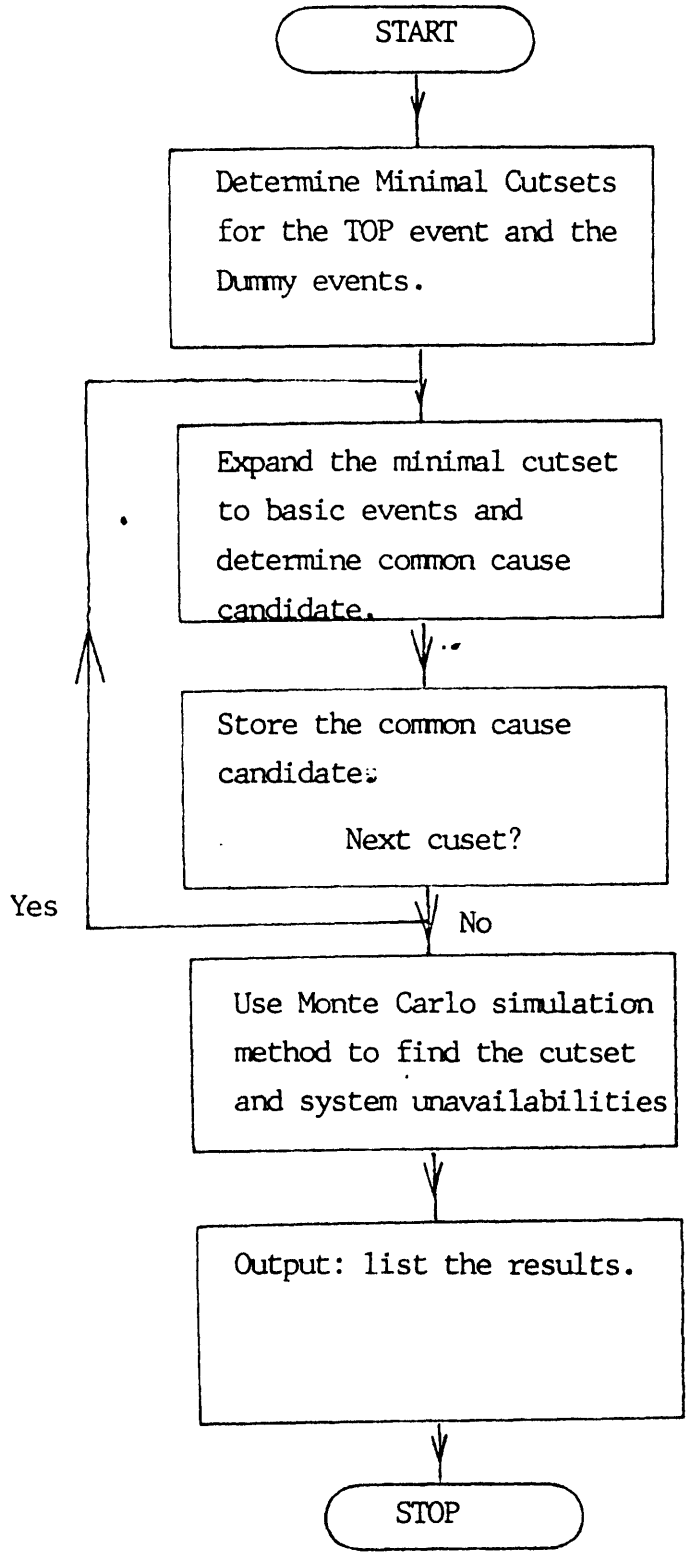


TABLE XVII

MOBB WITH METHOD OF MOMENTS

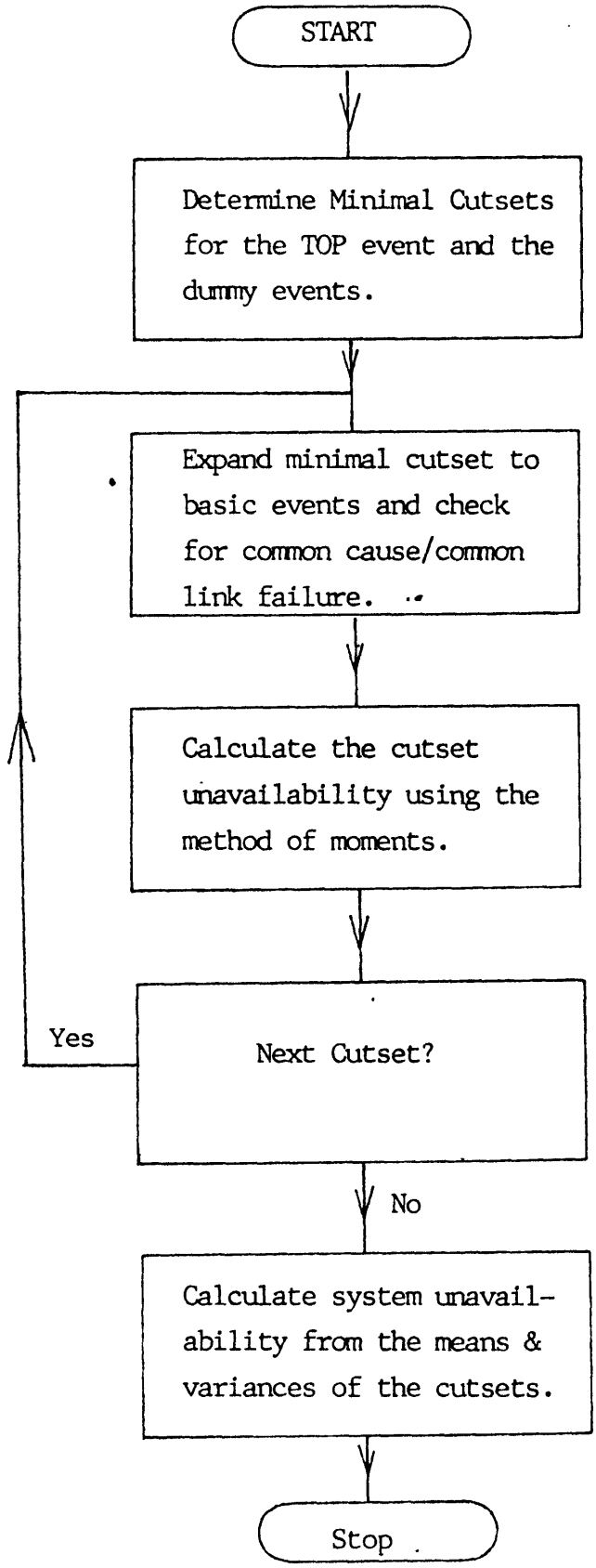


TABLE XVIII

MATHEMATICAL FORMULAE FOR VARIOUS LOGNORMAL FUNCTIONS EMPLOYED IN METHOD OF MOMENTS

Log-normal Probability Distribution $S_1(x|\mu,\sigma)$

$$S_1(x|\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} \exp[(\log(x)-\mu)^2/(-2\sigma^2)] \qquad 0 < x < \infty$$

$$= 0 \qquad \text{otherwise}$$

mth Moment $= \exp[m\mu + m^2\sigma^2/2]$

Bounded Log-normal Probability Distribution $S_b(x|\mu,\sigma)$

$$S_b(x|\mu,\sigma) = \frac{1}{x(1-x)\sigma\sqrt{2\pi}} \exp[(\log(\frac{1}{1-x})-\mu)^2/(-2\sigma^2)] \qquad 0 < x < 1$$

$$= 0 \qquad \text{otherwise}$$

mth Moment $= \int_0^1 x^m S_b(x|\mu,\sigma)\, dx$

Truncated Log-normal Probability Distribution $S_t(x|\mu,\sigma)$

$$S_t(x|\mu,\sigma) = \frac{C}{x\sigma\sqrt{2\pi}} \exp[(\log(x)-\mu)^2/(-2\sigma^2)] \qquad 0 < x < 1$$

$$= 0 \qquad \text{otherwise}$$

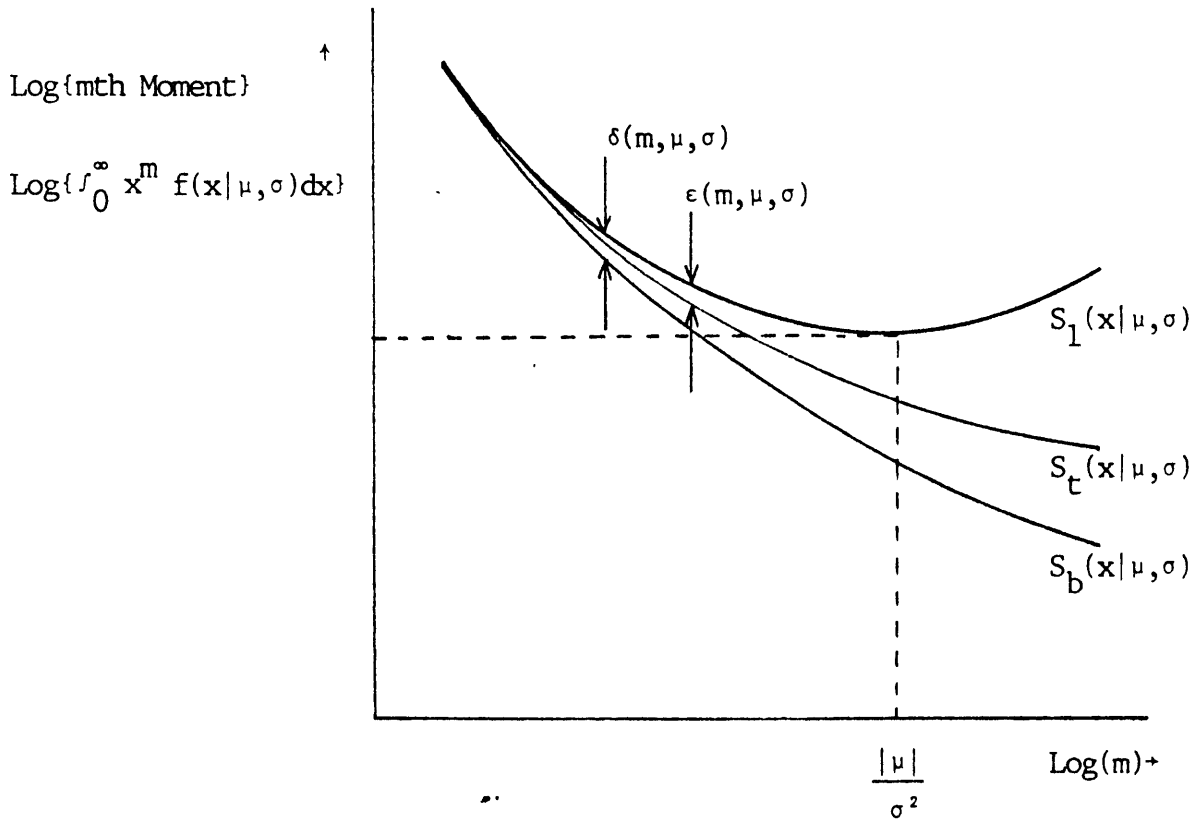
where C is the normalization factor

$$C^{-1} = \int_0^1 S_1(x|\mu,\sigma)\, dx$$

mth Moment $= \int_0^1 x^m S_t(x|\mu,\sigma)\, dx$

Figure 9

Behavior of Various Lognormal Function Options



$$\delta(m,\mu,\sigma) = \frac{|\int_0^1 x^m S_b(x|\mu,\sigma)dx - \int_0^\infty x^m S_1(x|\mu,\sigma)dx|}{|\int_0^1 x^m S_b(x|\mu,\sigma)dx|}$$

$$\epsilon(m,\mu,\sigma) = \frac{|\int_0^1 x^m S_t(x|\mu,\sigma)dx - \int_0^\infty x^m S_1(x|\mu,\sigma)dx|}{|\int_0^1 x^m S_t(x|\mu,\sigma)dx|}$$

TABLE XIX

SAMPLE UNAVAILABILITY EXPRESSION: RESULTS OF COMPARISON

Boolean Expression for system unavailability:

$S = X_1 + X_2X_3 + X_4X_5 + X_6$

Basic Events	Median of failure probabilities
X_1	$1x10^{-3}$
X_2	$3x10^{-2}$
X_3	$1x10^{-2}$
X_4	$3x10^{-2}$
X_5	$1x10^{-2}$
X_6	$3x10^{-3}$

	RF=3		RF=10	
Method	Mean	Variance	Mean	Variance
Discrete	$5.936x10^{-3}$	$7.2x10^{-6}$	$1.49x10^{-2}$	$2.14x10^{-4}$
Method of Moments: S_1	$5.936x10^{-3}$	$9.4x10^{-6}$	$1.491x10^{-2}$	$8.76x10^{-4}$
S_b	$5.933x10^{-3}$	$9.4x10^{-6}$	$1.410x10^{-2}$	$3.97x10^{-4}$
S_t	$5.938x10^{-3}$	$9.4x10^{-6}$	$1.424x10^{-2}$	$4.80x10^{-4}$
Monte Carlo Sample (3000)	$5.955x10^{-3}$	$8.6x10^{-6}$	$1.426x10^{-2}$	$3.97x10^{-4}$
Sample (1200)	$5.996x10^{-3}$	$9.3x10^{-6}$	$1.477x10^{-2}$	$4.73x10^{-4}$
Discrete (1200)	$5.788x10^{-3}$	$6.3x10^{-6}$	$1.402x10^{-2}$	$1.89x10^{-4}$

Even so, the differences seem relatively minor when plotted (Figure 10); yet the S_b approximation appears easier to implement for numerical calculation reasons, and is most accurate. Nevertheless, any choice involving the use of the Method-of-Moments is more efficient than Monte Carlo simulation; a factor of at least 10 in savings in computation time can be expected based on this project's experience in running the code.* Supporting material is provided in Appendices A-B of this report.

IV. Cutset Susceptibility Concept for Common Cause Analysis

A separate analysis technique for analyzing common cause failures was applied in this project, with results compared to that of MOBB for treating cutset uncertainty. A simple code for performing discrete probability distribution (DPD) arithmetic was developed and applied to a sample problem, that of the warehouse fire protection system (FPS) analyzed earlier (see section B.1), but this time, for seismic contribution to total system unavailability. Finally, a comparison of uncertainty treatment is made with that of the MOBB code.**

A. Method Description

As described in section II.A: "Dependent Failure Analysis", so-called "external" events, such as earthquakes, floods, and fires, are a type of dependent failure or common cause failure mechanism. The method which has been developed to deal with seismic

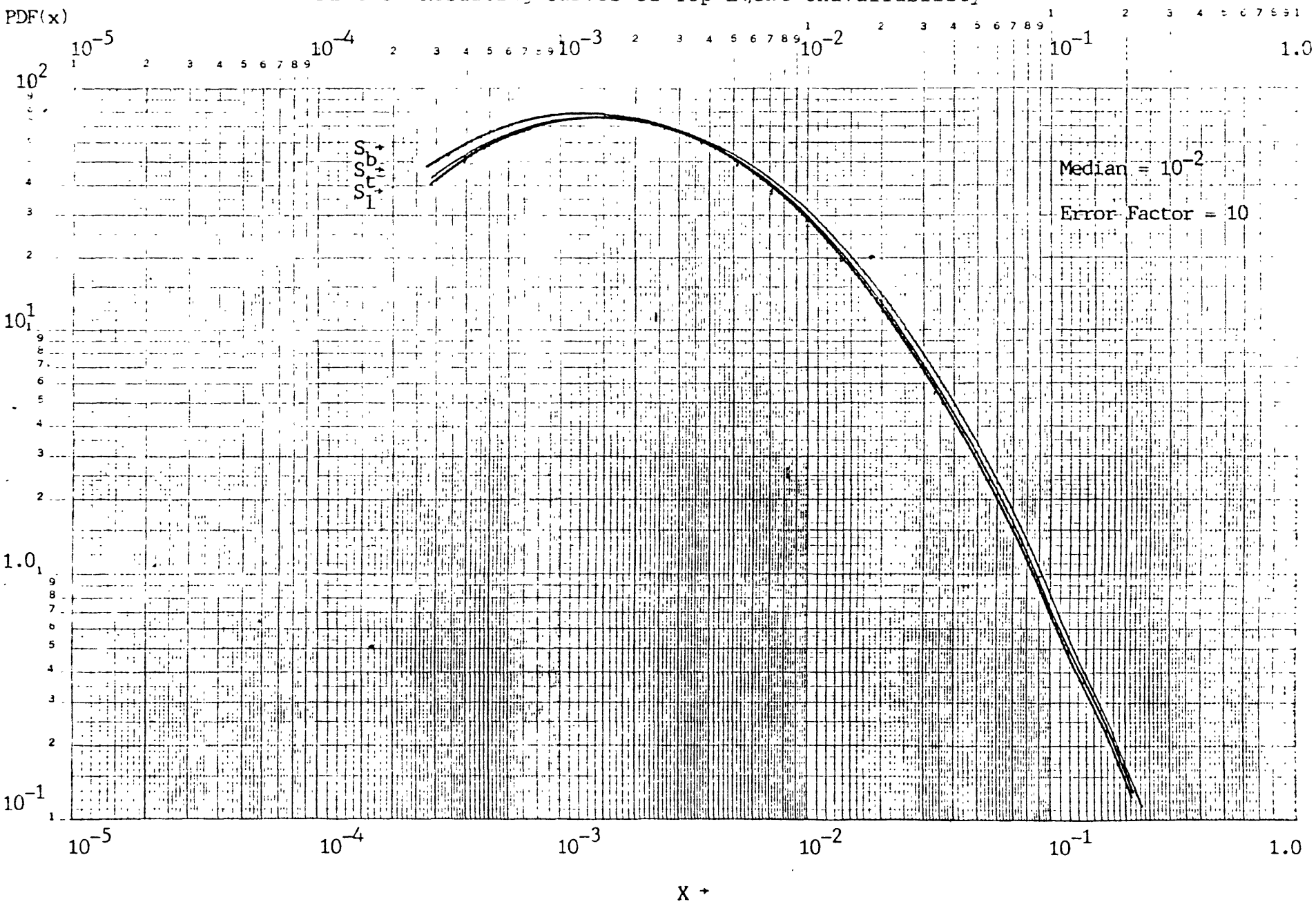
*This result supports the finding of Jackson and Lee, et. al. [21] and Bier [22].

**This work would be more fully developed in the follow-up proposal for next year (see Appendix F.4 for proposal description.

K+E LOGARITHMIC 3 x 5 CYCLES KEUFFEL & ESSER CO. 46 7522

Figure 10

Plot of Resulting Curves of Top Event Unavailability



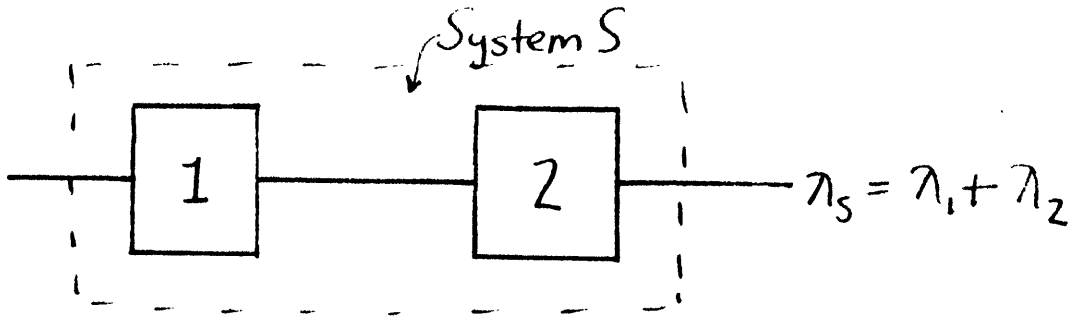
risk quantification in nuclear plant risk assessments can, in fact, be applied to quantify other dependent failure mechanisms of the "internal" type (i.e., humidity, pressure, temperature, vibration, human error, etc.). The only constraint in the application is that due to data collection, yet the seismic risk methodology allows for a clear presentation of the data uncertainty that perhaps makes it a more preferable approach to other methods.

The basic idea would be to identify all system cutsets that are common cause candidates, thus first employing the MOCUS-BACFIRE II package, and then substitute for the Beta-Factor CCF quantification package with the separate code developed here employing the seismic risk method approach. The mathematical details of the approach are now described.

A.1. Treatment of Uncertainty Using DPD Arithmetic (from PLG Handbook, ref. (2))

In calculations of real world phenomena, there is almost invariably significant uncertainty in the numerical values of parameters. In these calculations, numerical quantities can be replaced by probability distributions and mathematical operations between these quantities should be replaced by analogous operations between probability distributions.

In risk and reliability calculations, it is often necessary to perform various operations between probability or frequency distributions. Take the example of a simple series system of two components with failure rates λ_1 and λ_2. Then the system failure rate, λ, can be defined as:



If we express our state-of-knowledge about the component failure rates with probability density functions, $P_i(\lambda_i)$, then the probability distribution for λ_s is the sum:

$$P_s(\lambda_s) = P_1(\lambda_1) + P_2(\lambda_2) \tag{19}$$

where the symbol "+" between two distributions is understood to stand for the convolution operation:

$$P_s(\lambda_s) = \int_0^\infty P_1(\lambda_1)P_2(\lambda_s-\lambda_i)d\lambda_1 \tag{20}$$

assuming states-of-information P_1 and P_2 are independent.

For a parallel system:

$$\lambda_s = \lambda_1 \times \lambda_2 \tag{21}$$

$$P_s(\lambda_s) = P_1(\lambda_1) \times P_2(\lambda_2) \tag{22}$$

where "x" corresponds to the multiplicative convolution operation:

$$P_s(\lambda_s) = \int_0^\infty P_1(\lambda_1)P_2(\frac{\lambda_s}{\lambda_1}) \frac{d\lambda_1}{\lambda_1} \tag{23}$$

Combinations far more complicated than this occur routinely in risk and reliability work. Usually, Monte Carlo can be used to compute these combinations. An alternate approach is the method of discrete probability distributions (DPDs).

Rules of DPD Arithmetic

Let X be an ordinary scalar variable, and let X_1, X_2 ... X_n denote particular discrete values of x.

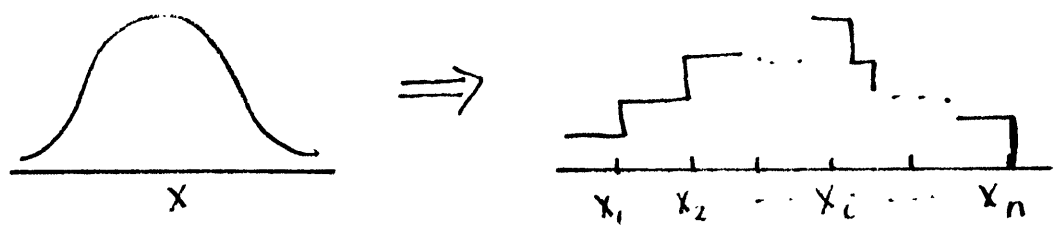
Let P_1, P_2 ... P_n be the associated probability values such that:

$$\sum_{i=1}^{n} P_i = 1 \tag{24}$$

Then the set of doublets

$$\langle P_1, X_1\rangle, \langle P_2, X_2\rangle \ldots \langle P_n, X_n\rangle = \langle P_i, X_i\rangle \tag{25}$$

is the DPD and is an approximation to a continuous pdf.



Probabilistic Addition

Suppose $Z = X + y$, $\quad x = \langle P_i, X_i\rangle$, $\quad y = \langle q_i, y_i\rangle$ (26)

Suppose X and y are independent (they are based on independent states of information:

Then

$$Z = \langle P_i, X_i\rangle + \langle q_j, y_i\rangle \tag{27}$$

$$= \langle P_i q_j, X_i + y_i\rangle \tag{28}$$

this DPD represents
our state-of-knowledge on Z

$$= \langle r_{ij}, Z_{ij}\rangle \tag{29}$$

where $r_{aj} = P_i q_j$, $Z_{ij} = X_i + y_j$ (30)

Example:

$$X = \{<.1,-1> <.5,1> <.4, 2>\} \tag{31}$$

$$y = \{<.2,5> <.8,10>\} \tag{32}$$

$$Z = \{<.02,4> <.1,6> <.08,7> <.08,9> <.4,11> <.32,12>\} \tag{33}$$

$$= \{<P_i q_j, X_i + y_j>\}$$

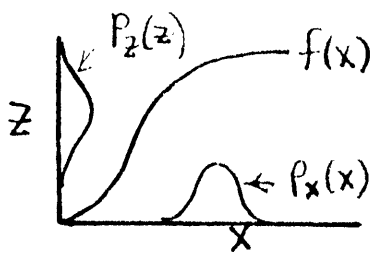
Multiplication

$$\{<P_i, X_i>\} \cdot \{<q_j, y_j>\} = \{<P_i q_j, X_i y_j>\} \tag{34}$$

Functional Definitions

Consider $Z = f(X)$, $X = \{<P_i, X_i>\}$ (35)

so $Z = \{<P_i, f(X_i)>\}$ (36)

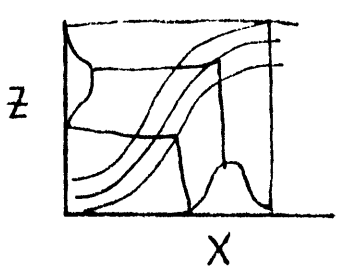


We enter the curve f(X) with a probability distribution for X and emerge with a distribution for Z.

Suppose now that f itself is also probabilistic (there is uncertainty on f). We can express quantitatively this uncertainty by setting out a series of different functional forms f_j and assigning probabilities to each:

$$f = \{<q_j, f_j>\} \; ; \; \sum_j q_j = 1. \tag{37}$$

Graphically:



We enter a probabilistic function with a probabilistic argument and emerge with a probabilistic output. If both X and f are probabilistic, then Z is:

$$Z = \{<P_i q_j,\ f_j(X_i)>\} \tag{38}$$

f is plotted as a "band"--a family of curves with P as a parameter.

Pitfalls

1. Nondistributivity of Probabilistic Operations

In ordinary arithmetic, if

$Q = X[y+Z]$ then

$Q = Xy + XZ$ distributivity

This does not hold for DPDs--pay careful attention to the sequencing of operations.

2. Independence and Dependence

Suppose $Z = 2X$: $X = \{<.2,1><.6,2><.2,3>\}$

Then $Z = \{<.2,2><.6,4>,<.2,6>\}$

Suppose $Z = X + X$

Then $Z = \{<.04,27><.24,3><.44,4><.24,5><.04,6>\}$

Thus $Z = 2X \neq Z = X + X$. The difference is that when we did the operation $X + X$, we treated the two distributions as if they were independent. THEY ARE NOT. Thus, we obtained compensating uncertainties and a more narrow distribution than we should have. This situation arises particularly in risk calculations between similar components.

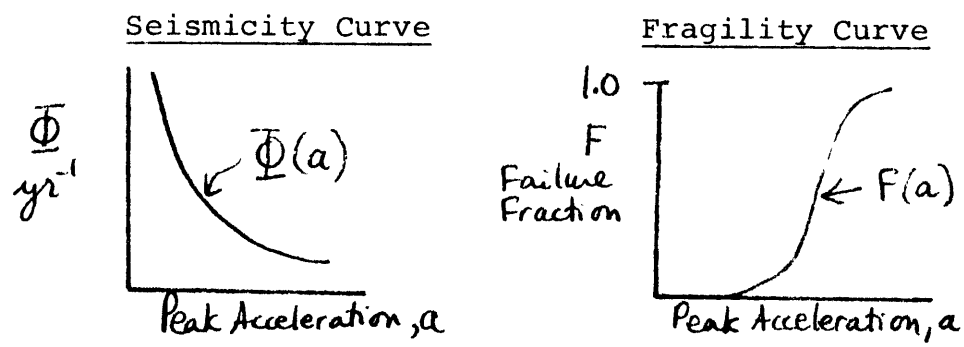
Thus, use $\lambda_s = 2\lambda_1$ for series system when components are identical ($\underline{\text{not}}$ $\lambda_s = \lambda_1 + \lambda_1$)

and $\lambda_s = \lambda_1^2$ for parallel system ($\underline{\text{not}}$ $\lambda_s = \lambda_1\lambda_1$)

A.2 Application of Method to Seismic Risk Calculations (2)

Suppose we have a specific structure, S, at a specific location, L, and wish to know the risk of collapse of this structure due to earthquake.

What we use is a "seismicity" curve and a "fragility" curve, as follows:



Assume that we run the experiment and knew the curve F(a) exactly. Suppose also that we had monitored the site L for millions of years and knew the curve $\Phi(a)$ exactly.

The frequency of structural failure due to earthquake would be given by:

$$\Phi_f = -\int_0^\infty \frac{d\Phi}{da} f(a)da \tag{39}$$

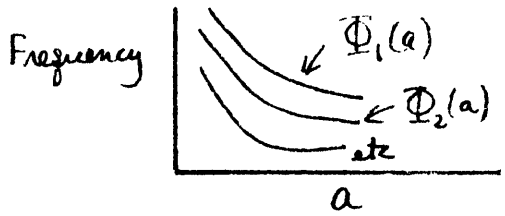
Probabilistic Calculation

We really do not know the seismicity curve $\Phi(a)$ exactly. Therefore, using the DPD idea, let us express our uncertainty in $\Phi(a)$ by putting forth a finite family of curves, $\Phi_i(a)$, and assigning to each a probability P_i:

Thus:

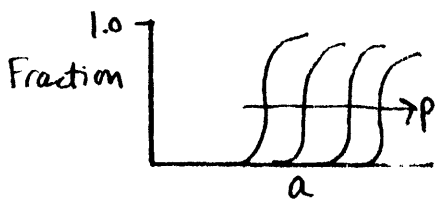
$$\Phi \equiv \left\{ \langle P_i, \Phi_i(a) \rangle \right\} \tag{40}$$

or graphically:



We also do not know the fragility curve exactly, so we express our state-of-knowledge about the fragility by writing a DPD:

$$F \equiv \left\{ \langle q_j, F_j(a) \rangle \right\} \tag{41}$$



Now, we perform the operation

$$\phi_f = -\int_0^\infty \frac{d\Phi}{da} F(a)da \tag{42}$$

using DPD arithmetic:

$$\phi_f = \left\{ \langle P_{ij}, \phi_{ij} \rangle \right\} \tag{43}$$

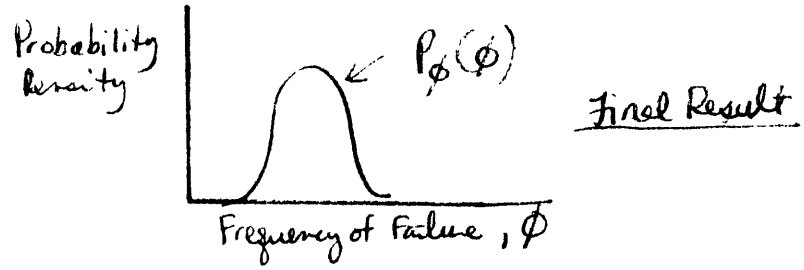
where

$$P_{ij} = P_i q_j \tag{44}$$

and

$$\phi_{ij} = -\int_0^\infty \left(\frac{d\phi_i}{da}\right) F_j(a)da \tag{45}$$

This is the "Probability of Failure Frequency" idea.



B. Code Description

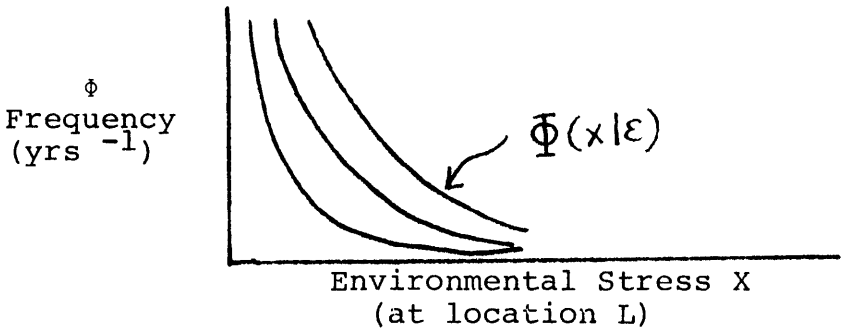
The method described in section (A) has been extended as follows to analyze "internal" common cause events. For each location in the plant, an "environmental stress" curve analagous to the seismicity curve in seismic risk analysis is defined by the user (see Figure 11). A family of such curves can be specified for the 95%, 50% and 5% confidence levels reflecting the analyst's uncertainty about the function $\Phi(X)$.

Next, the susceptibility of the cutset must be specified, again as a family of curves. This curve can be synthesized from knowledge concerning the individual component susceptibilities to each stress type, or on a multi-component, or cutset, level depending on the analyst's choice (see Figure 12). This curve must be defined as a function of whether one considers the system to be operating under normal or accident conditions, where "A" refers to the conditions considered (A_1 for "normal"; A_2 for "accident") and to the state-of-knowledge of the analyst who is specifying this curve.

The result of the analysis are probability density functions, or PDFs, about the frequency of failure (or unavailability) for each cutset as a function of the particular environmental stress type (see Figure 13).

Figure 11

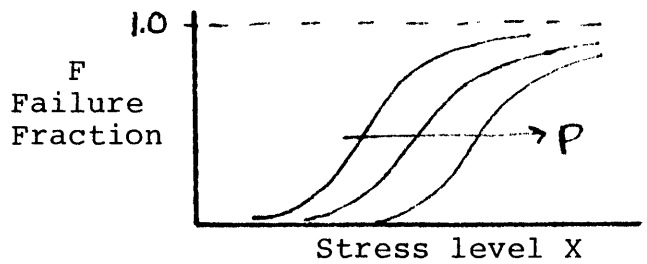
Environmental Stress Curve*



*Analogous to seismicity curve.

Figure 12

Cutset (Component) Environmental Susceptibility Curves*

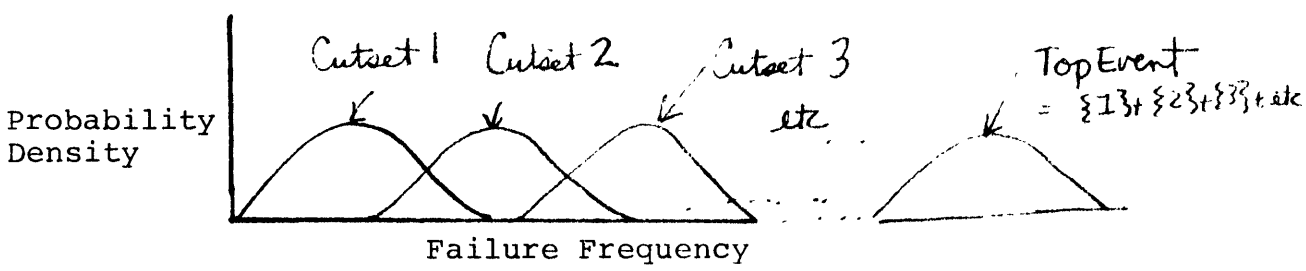


$F_j(X)$ = ability of cutset j to resist various levels of environmental stress X.

*Analogous to seismic fragility curves.

Figure 13

Result of Environmental Stress Analysis on System Cutsets



This method then produces a probability distribution on each cutset's unavailability, indicating uncertainties. The Boolean expression for the top event is then used, which will generally be just the sum of all the cutsets, so that the total system unavailability may also be expressed as a "probability of frequency" distribution.

Implementation of the actual calculational procedure employed in this approach is shown in Table XX.

C. Sample Problem: Warehouse FPS

The warehouse FPS of section III.B.1 was analyzed here for failure susceptibility to seismic events using the DPD code written in this project. The FPS was analyzed for three cases (see Figure 14):

S1 -- one pump train only (PTB) and no diesel generator

S2 -- one pump train with both diesel generator and off-site power

S3 -- both pump trains with both diesel generator and off-site power

The fault tree for each of the three system definitions was drawn (Figure 15) and the Boolean expression found for the top event (see Table XXI for System S3). Assumptions were made on the relative fragility of each cutset to seismic events (see Figures 16-22). The seismicity of the site was taken to be that of the Zion nuclear plant side in Chicago for representative purposes only (Figure 23).

Final results of the example calculations are shown in Figure 24 indicating the uncertainty of each cutset unavailability due to seismic events. Note that S1 has a median failure probability

TABLE XX

CUTSET FRAGILITY CONCEPT APPLIED TO ANALYZE CCF

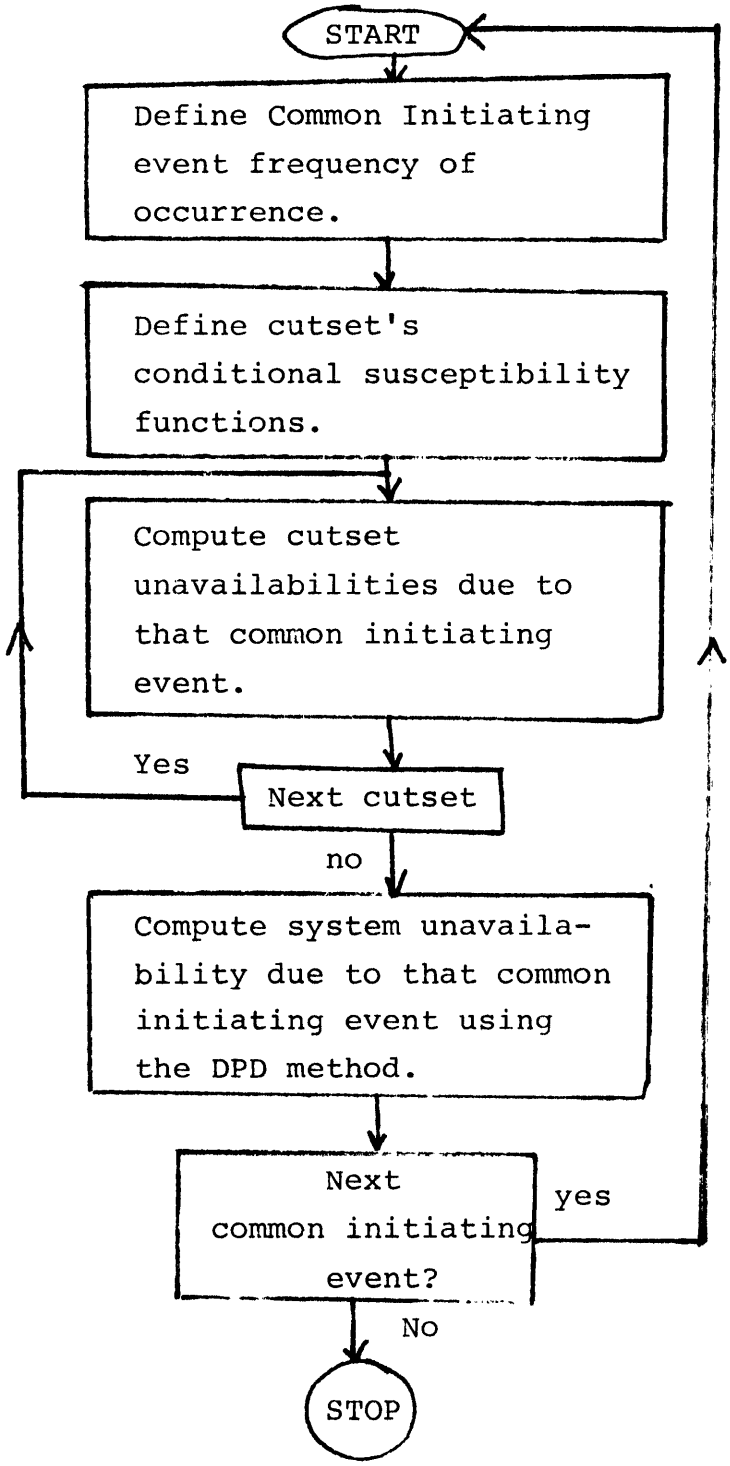
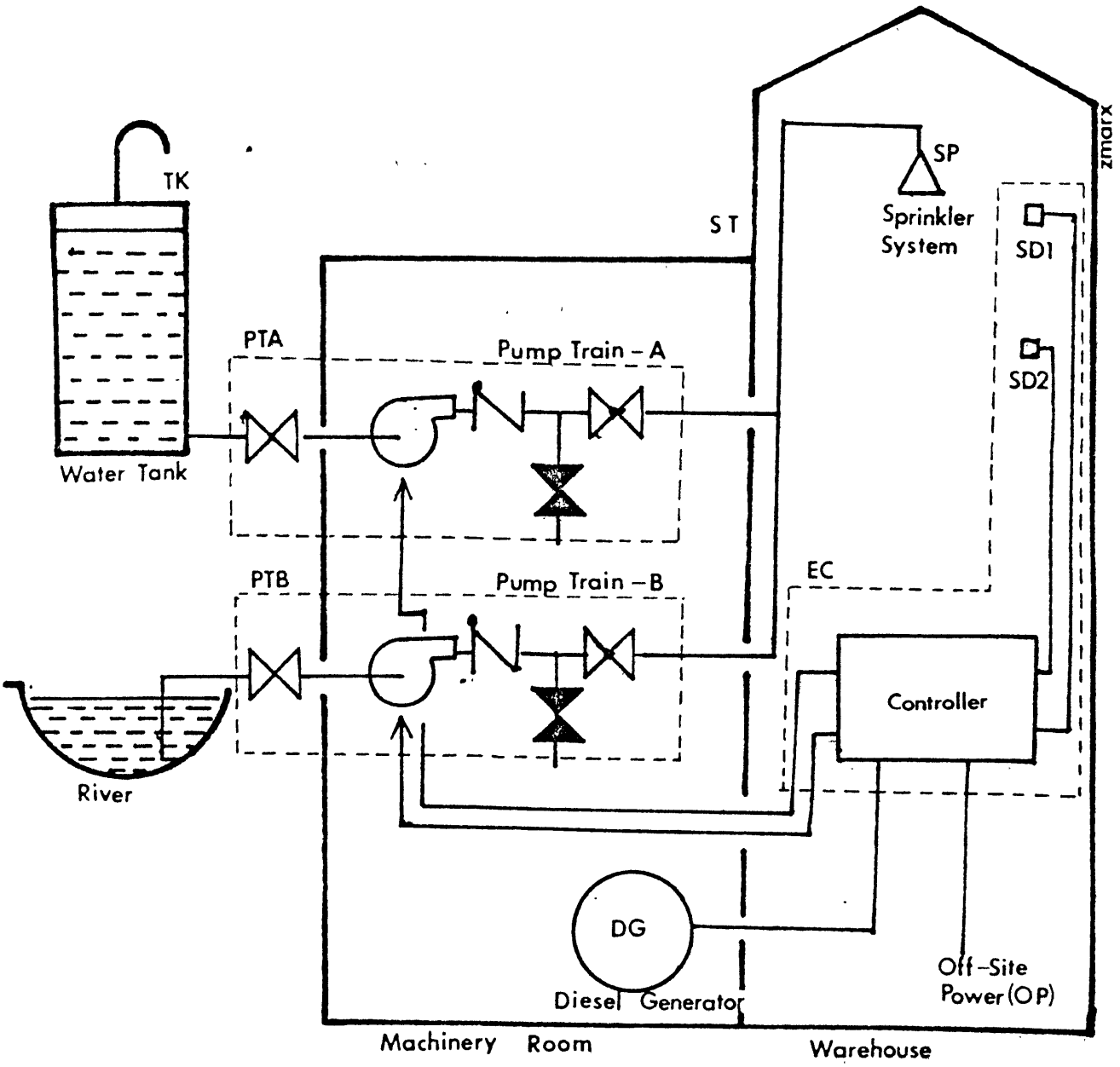


Figure 14

Modified Warehouse FPS with Added Diesel Generator



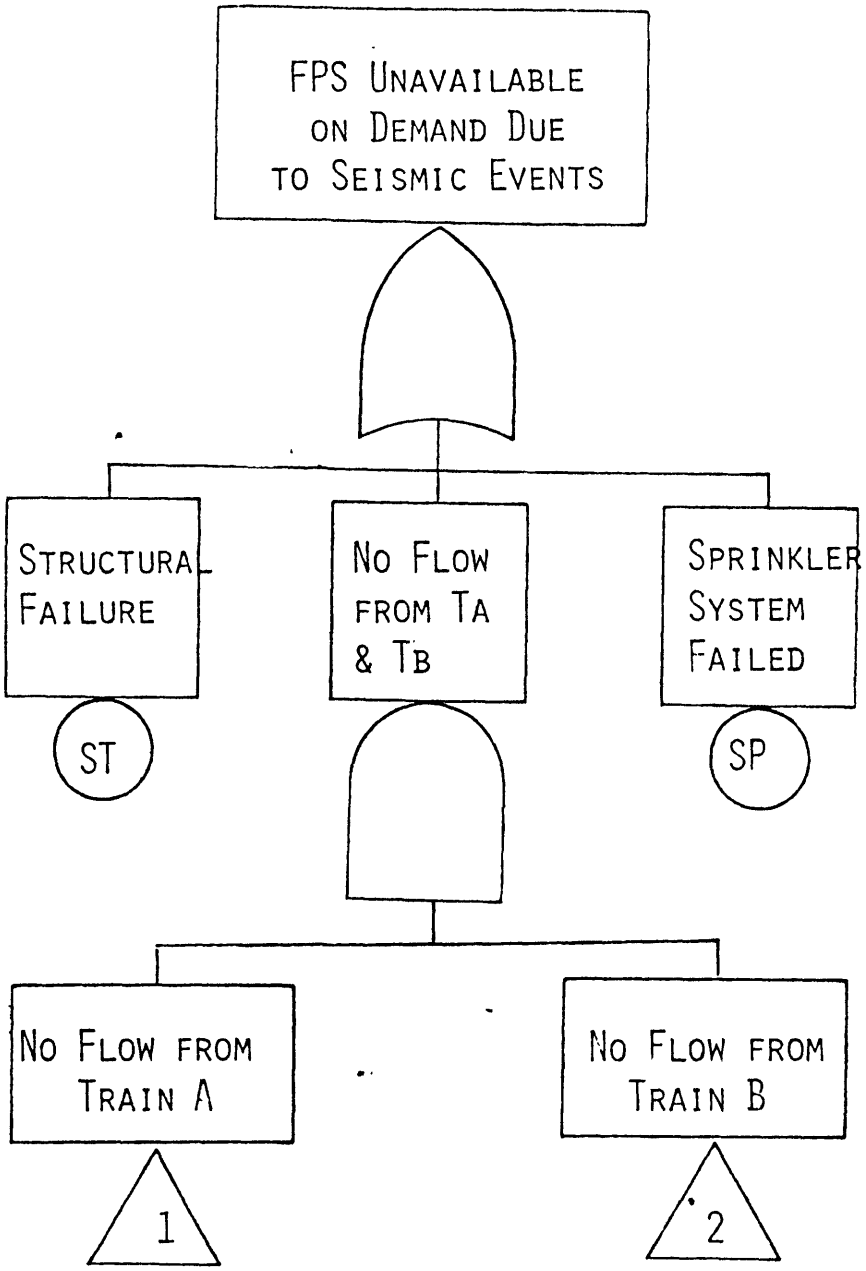


Figure 15

System Fault Tree (Sheet 1 of 3)

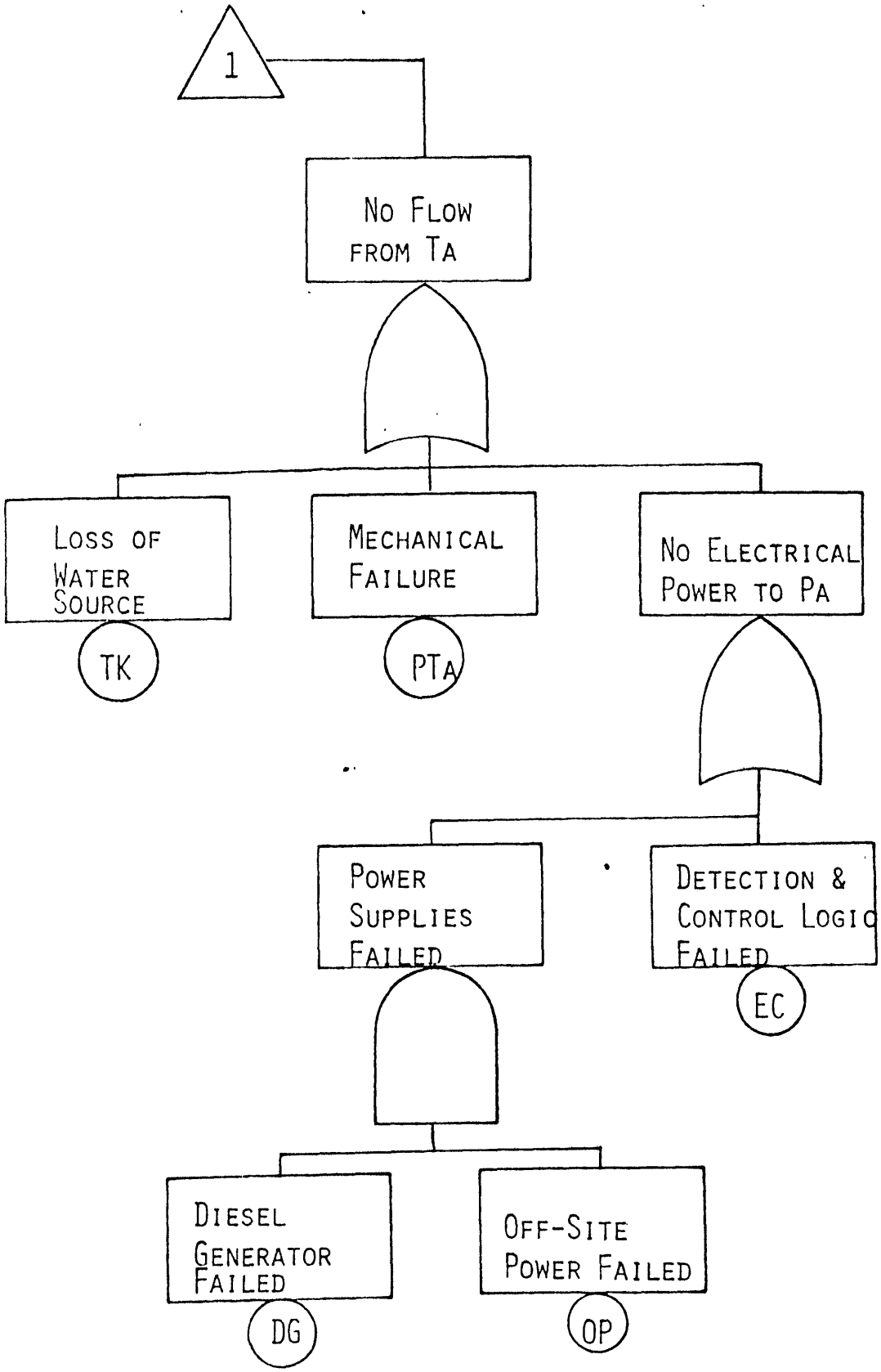


Figure 15 cont'd (Sheet 2 of 3)

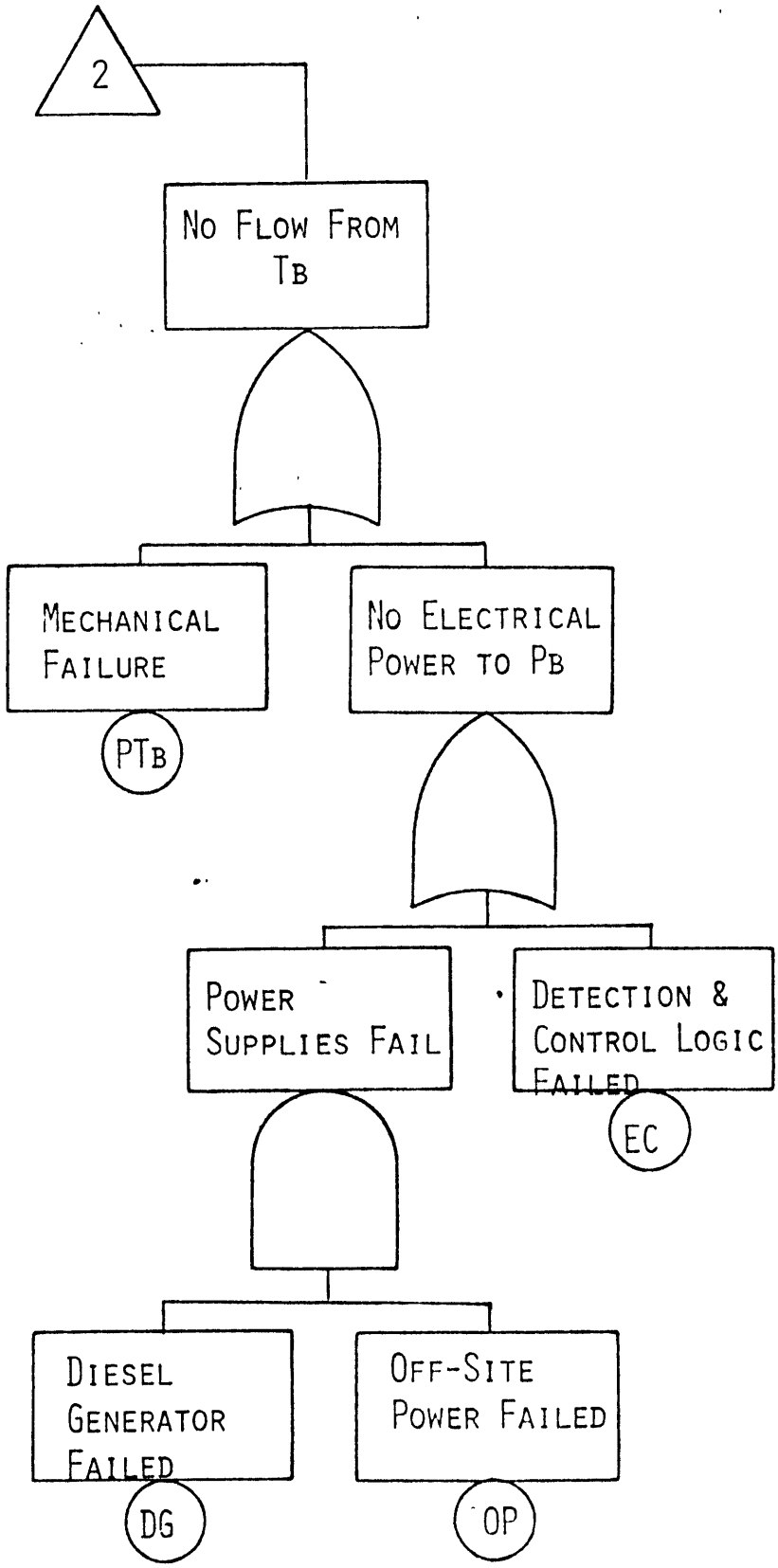


Figure 15 cont'd (Sheet 3 of 3)

TABLE XXI

CUTSET DEFINITION FOR FPS WITH
TOP EVENT BOOLEAN EXPRESSION (SYSTEM S3)

BOOLEAN EXPRESSION

$$F = ST + SP + T_A + T_B$$

WHERE $T_A = PT_A + TK + (EC + OP * DG)$

$T_B = PT_B + (EC + OP * DG)$

$$F = ST + SP + PT_A * PT_B + EC + OP * DG + TK * PT_B$$

F : SYSTEM FAILURE DUE TO SEISMIC EVENTS

THE FOLLOWING EVENTS ARE CONDITIONAL TO THE SEISMIC EVENTS:

ST : STRUCTURE (BUILDING AND SUPPORTING STRUCTURE FOR COMPONENTS TO ATTACH ON)

SP : SPRINKLING SYSTEM

T_A : PUMP TRAIN A

T_B : PUMP TRAIN B

PT_A: PUMP A AND ASSOCIATED VALVES AND PIPING

PT_B: PUMP B AND ASSOCIATED VALVES AND PIPING

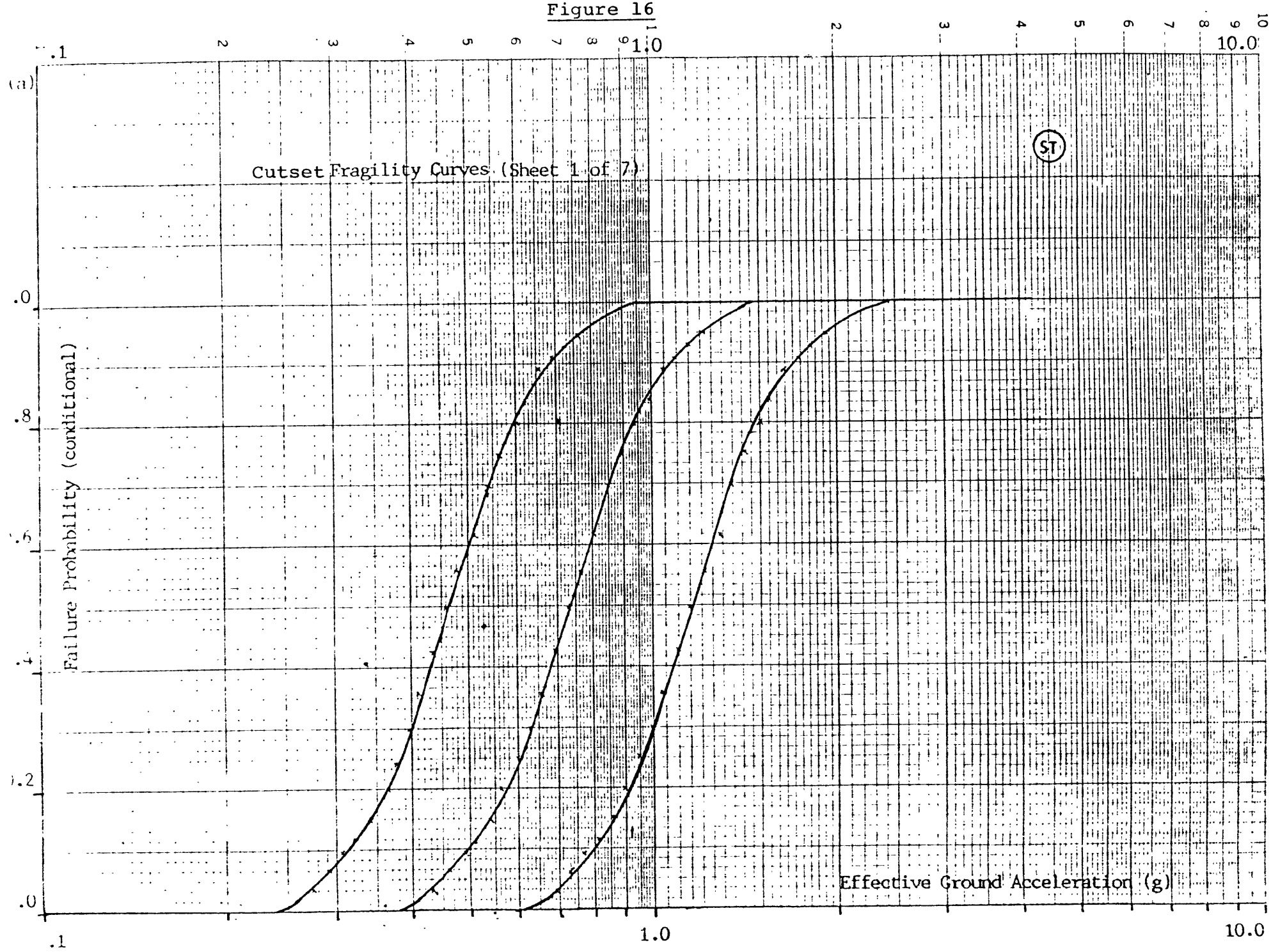
TK : WATER STORAGE TANK

OP : OFF-SITE POWER SUPPLIES

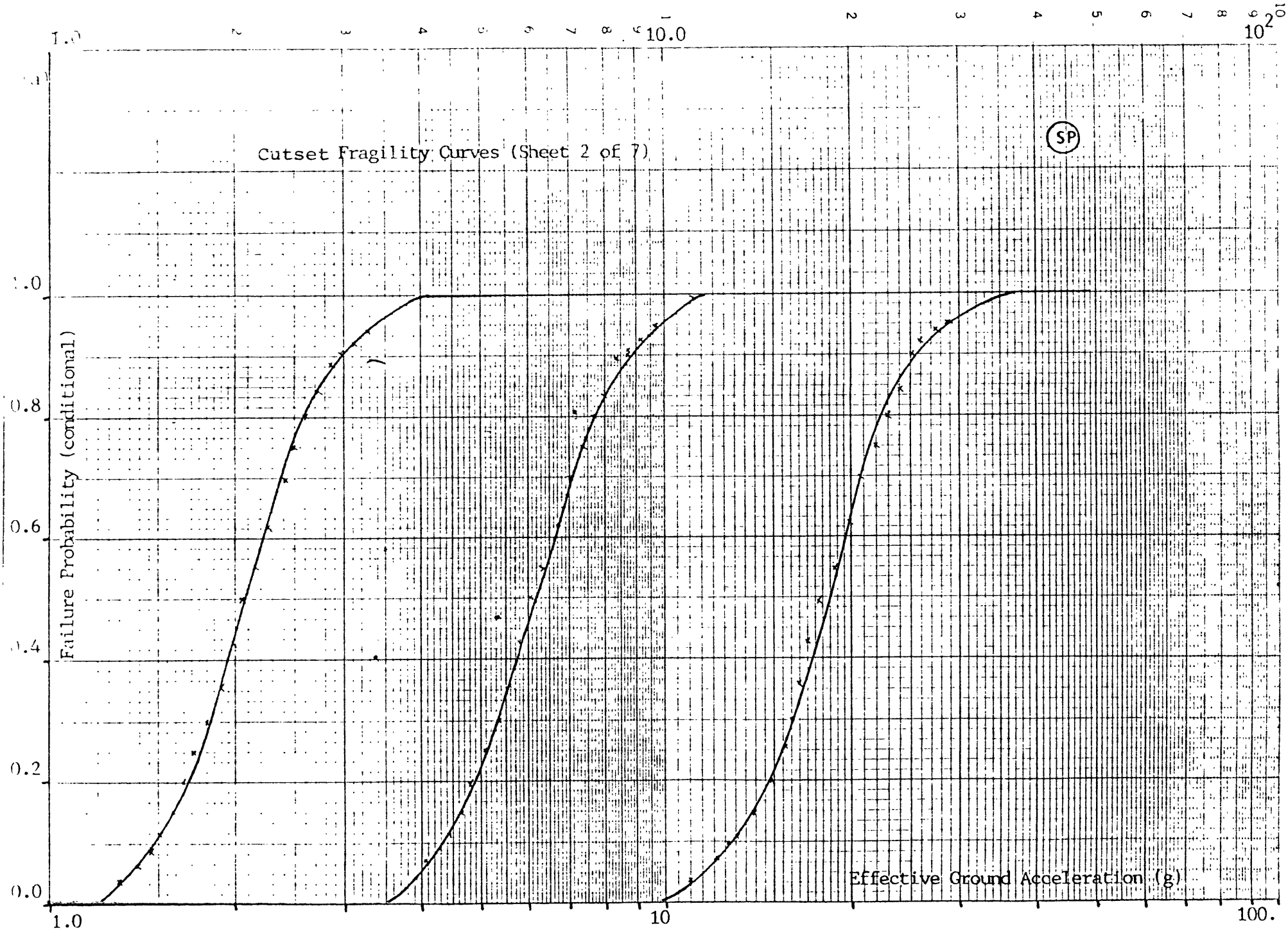
DG : DIESEL GENERATOR

EC : ELECTRONIC DETECTION AND CONTROL SYSTEM

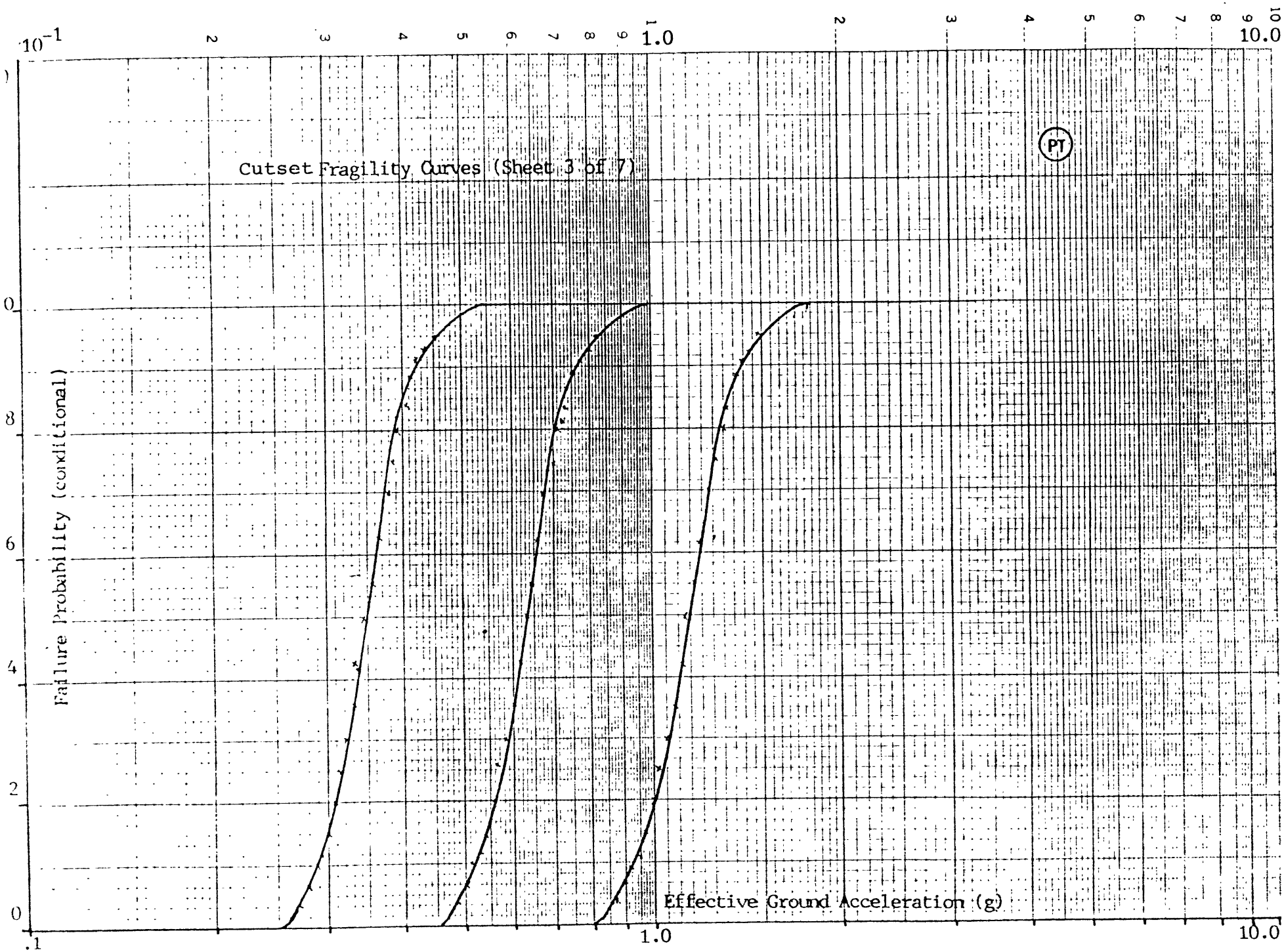
Figure 16


SEMI-LOGARITHMIC 2 CYCLES X 84 DIVISIONS
46 5050zmarx
Cutset Fragility Curves (Sheet 1 of 7)
ST
(a)
Failure Probability (conditional)
Effective Ground Acceleration (g)
.1
1.0
10.0
.0
.8
.6
.4
.2
.0

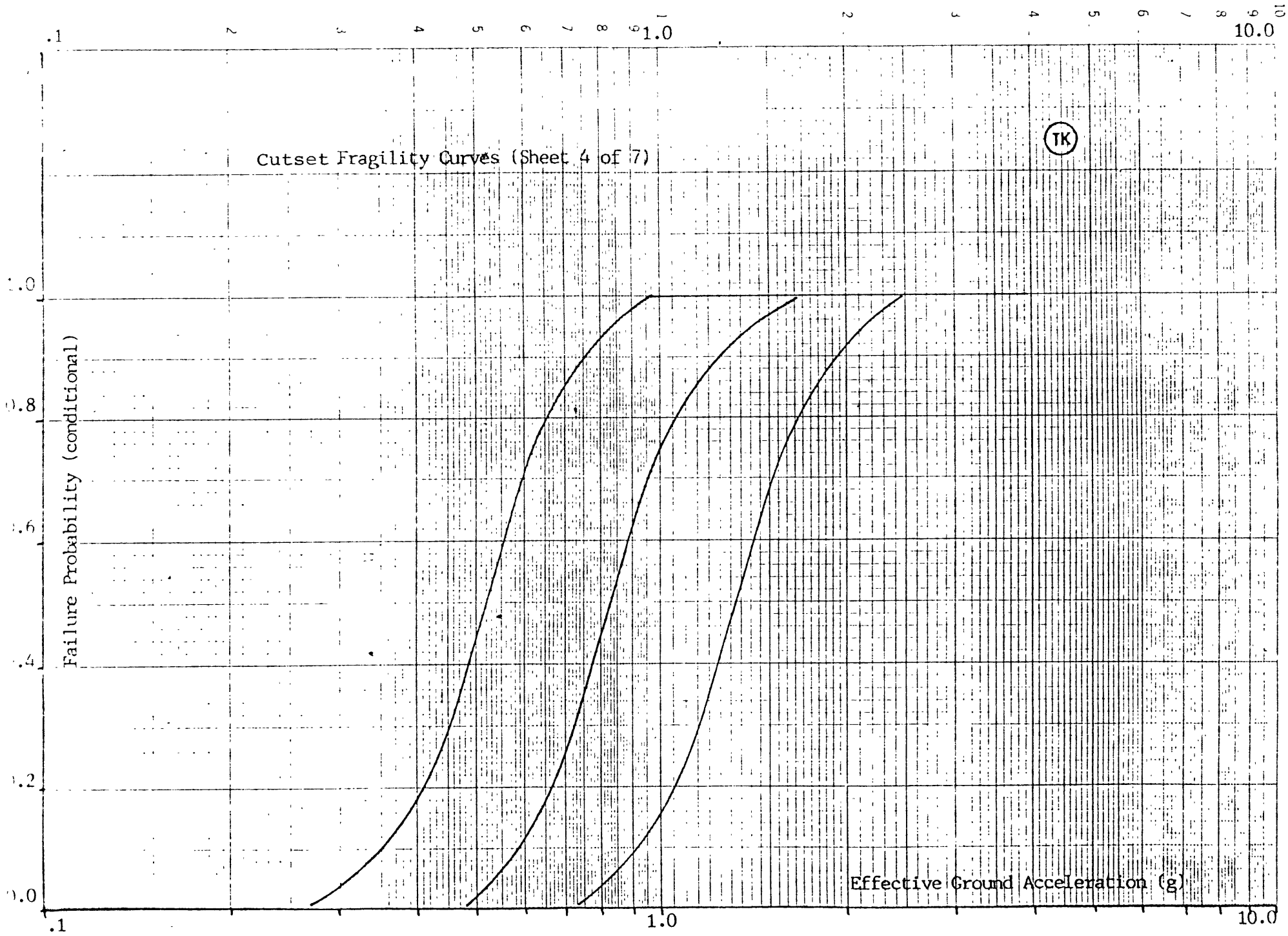
46 5050zmarx

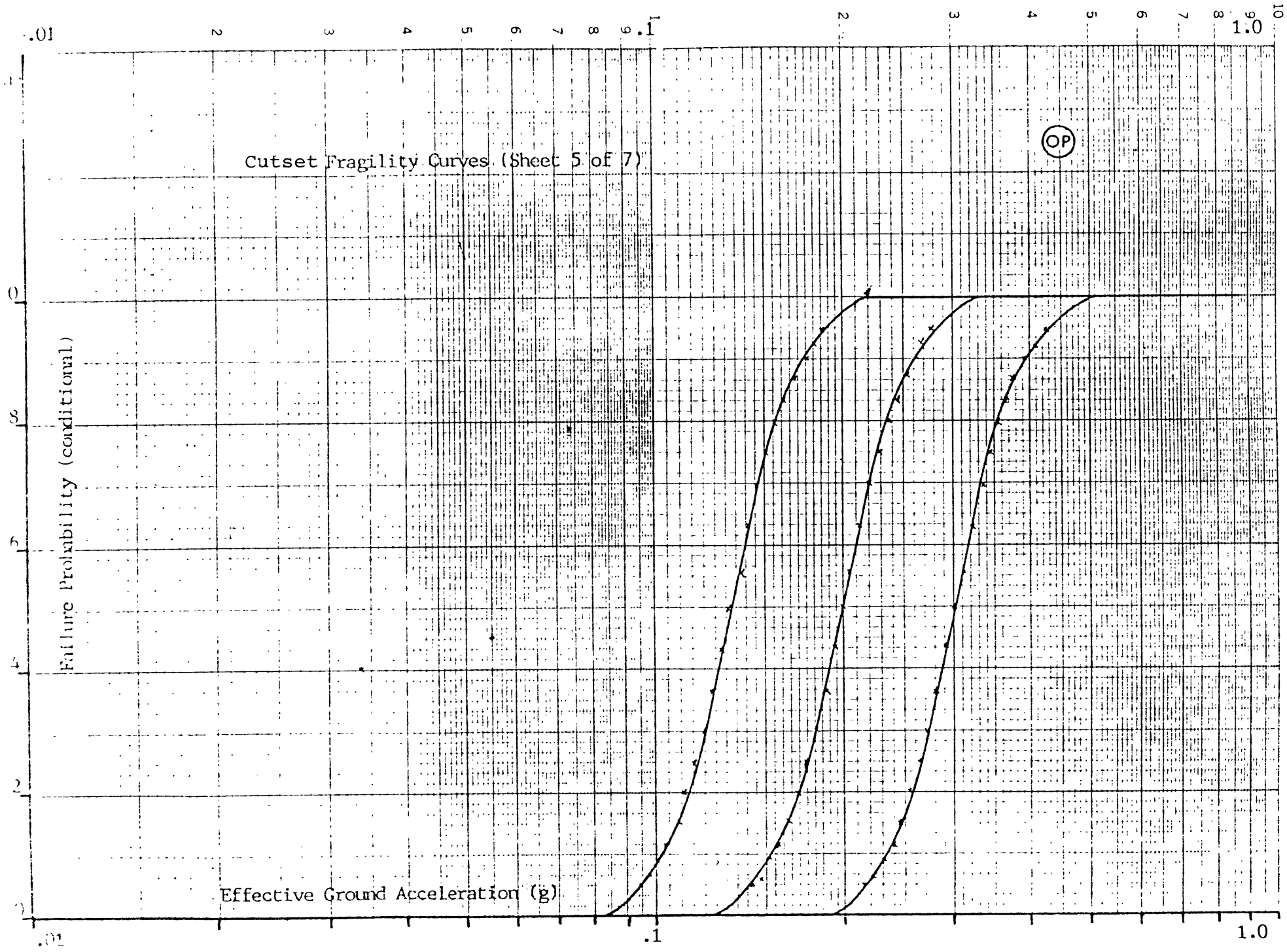


K+E SEMI-LOGARITHMIC 2 CYCLES X 84 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 5050zmarx



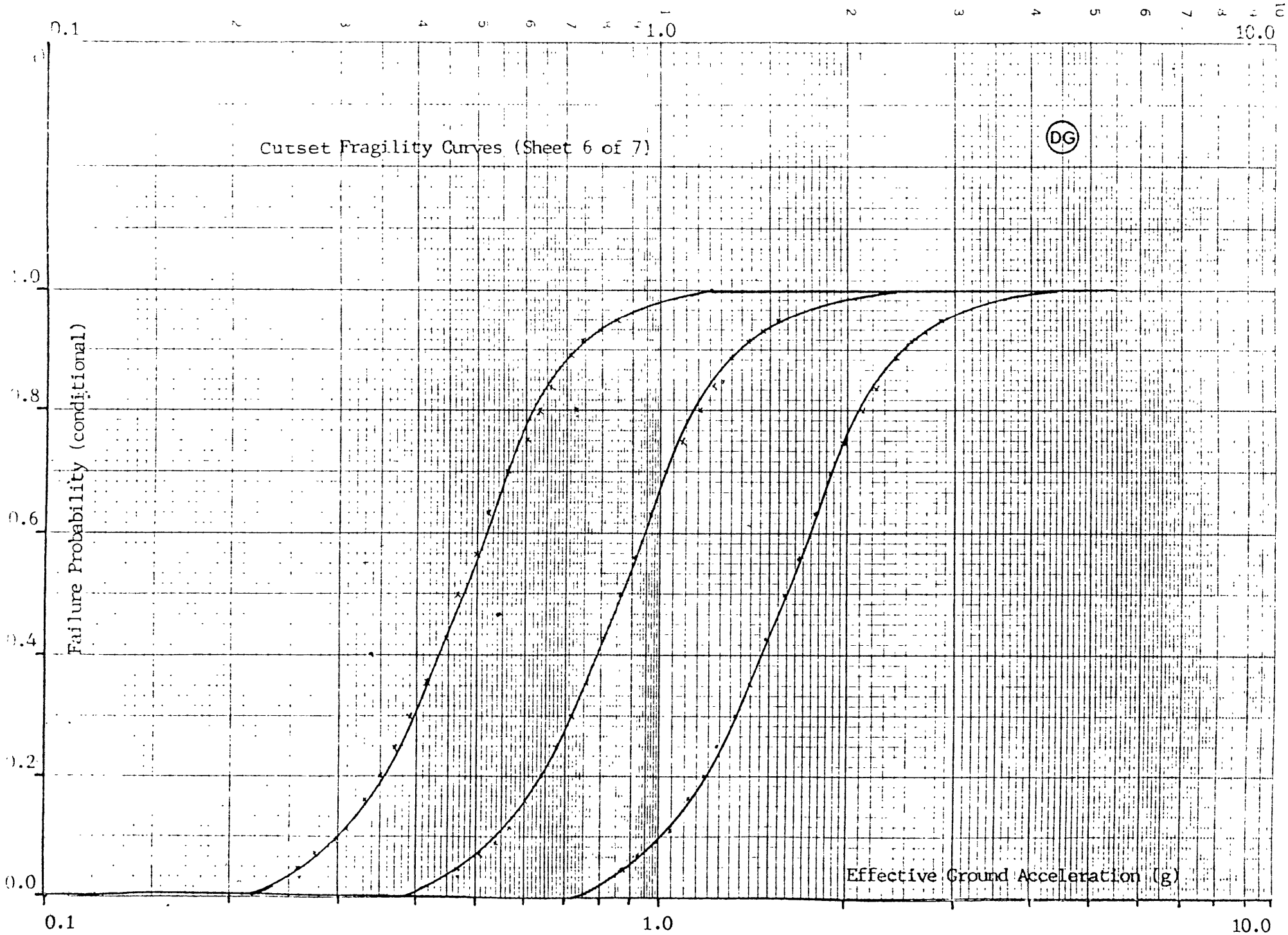
SEMI-LOGARITHMIC
KEUFFEL & ESSER CO.
46 4970zmarx




Cutset Fragility Curves (Sheet 5 of 7)
OP
Failure Probability (conditional)
Effective Ground Acceleration (g)
.01
.1
1.0

SEMI-LOGARITHMIC 2 CYCLES X 84 DIVISIONS
KEUFFEL & ESSER CO.

46 5050zmarx



K&E SEMI-LOGARITHMIC 2 CYCLES X 84 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 5050zmarx

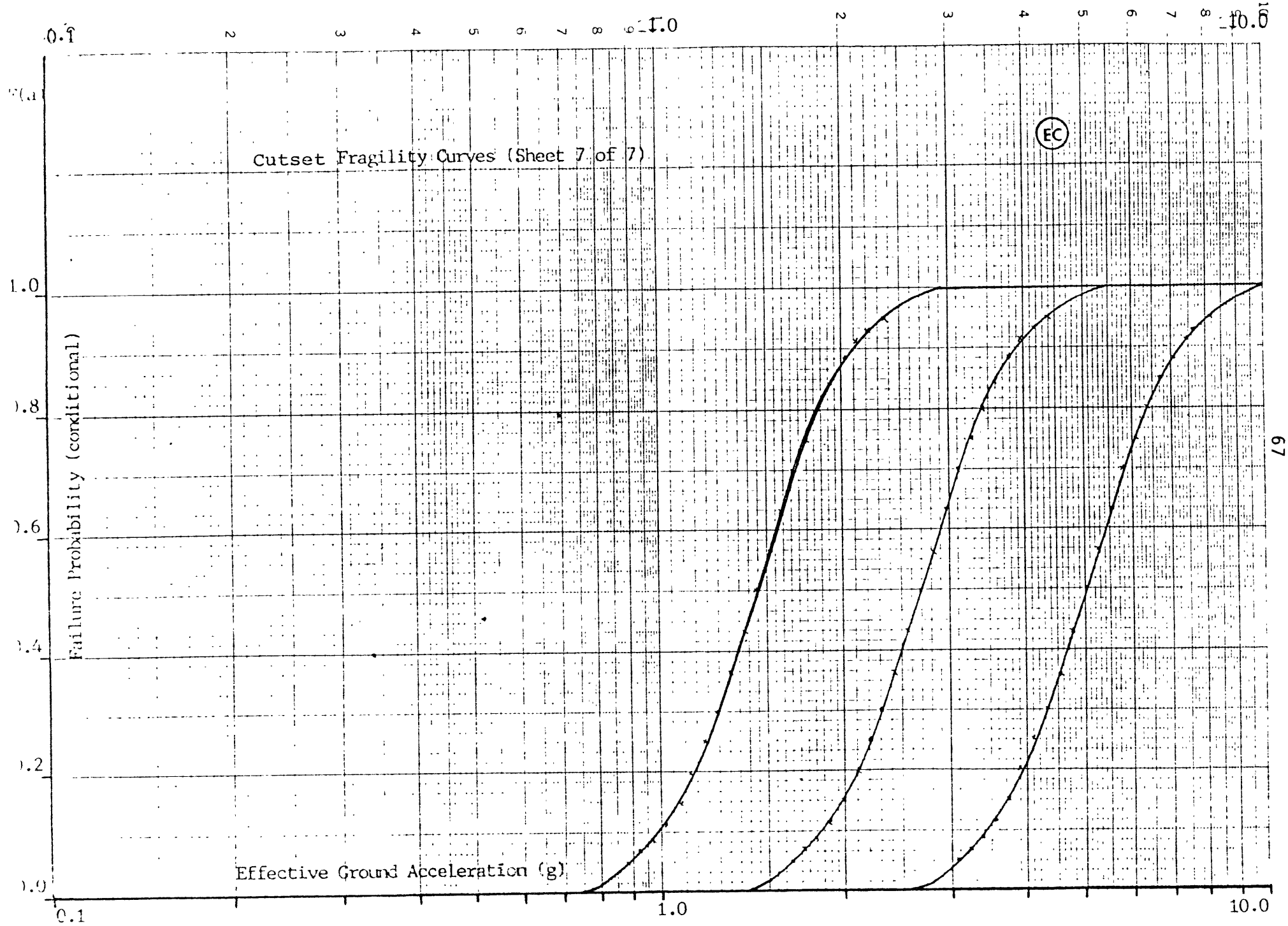
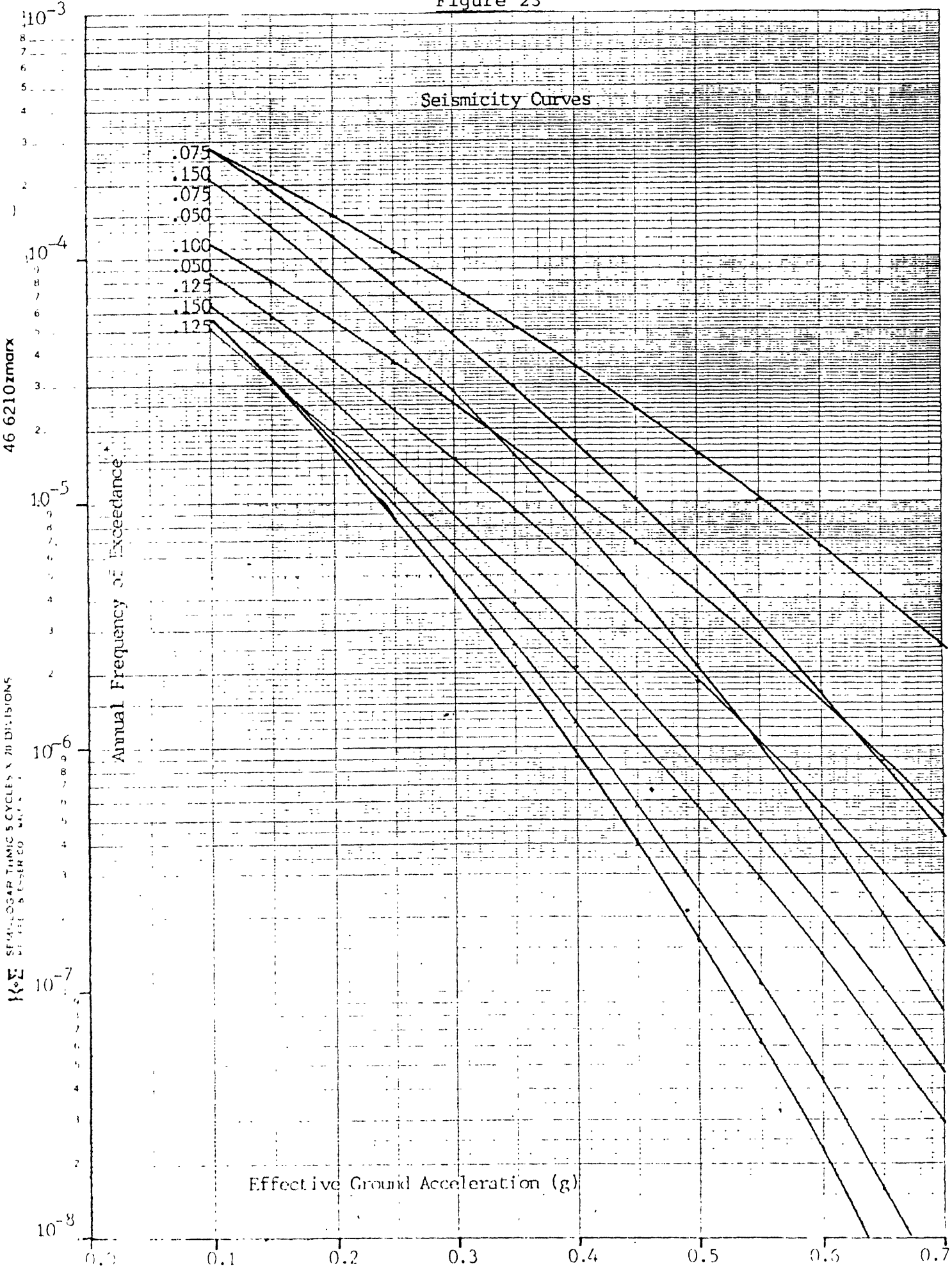
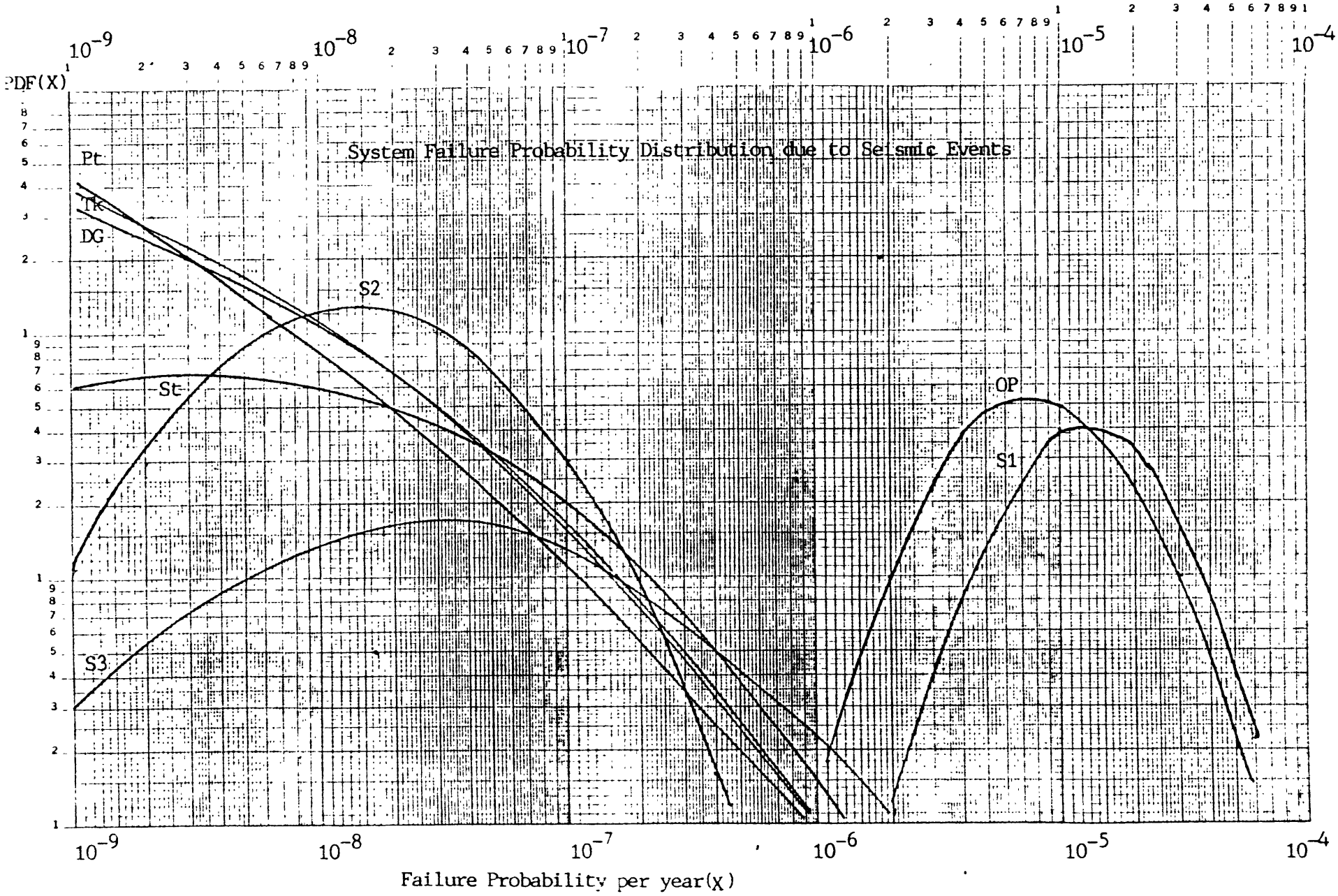


Figure 23


Seismicity Curves
.075
.150
.075
.050
.100
.050
.125
.150
.125
Annual Frequency of Exceedance
Effective Ground Acceleration (g)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
46 6210zmarx

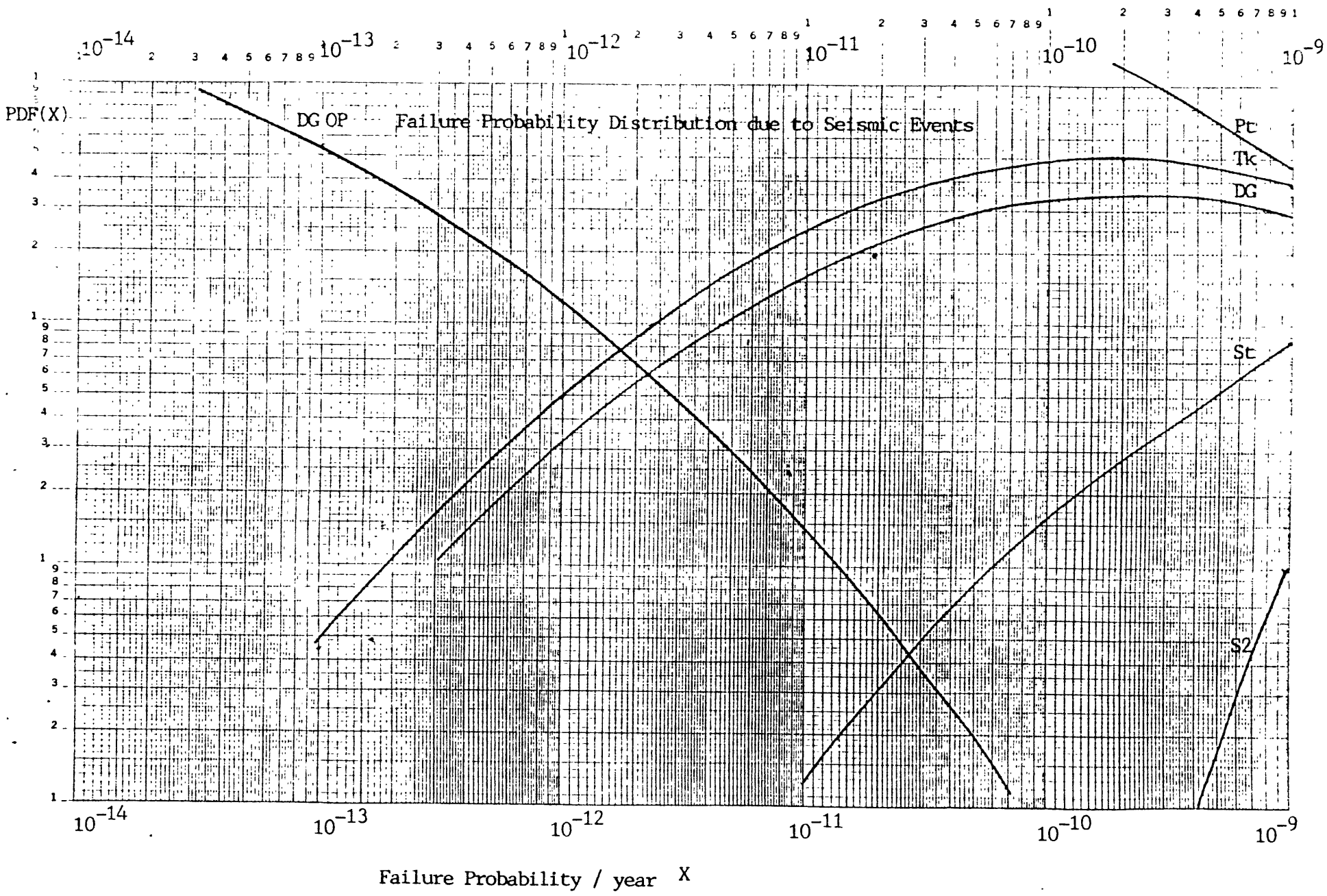
K+E LOGARITHMIC 3 x 5 CYCLES
KEUFFEL & ESSER CO MADE IN U.S.A.
46 7522

Figure 24



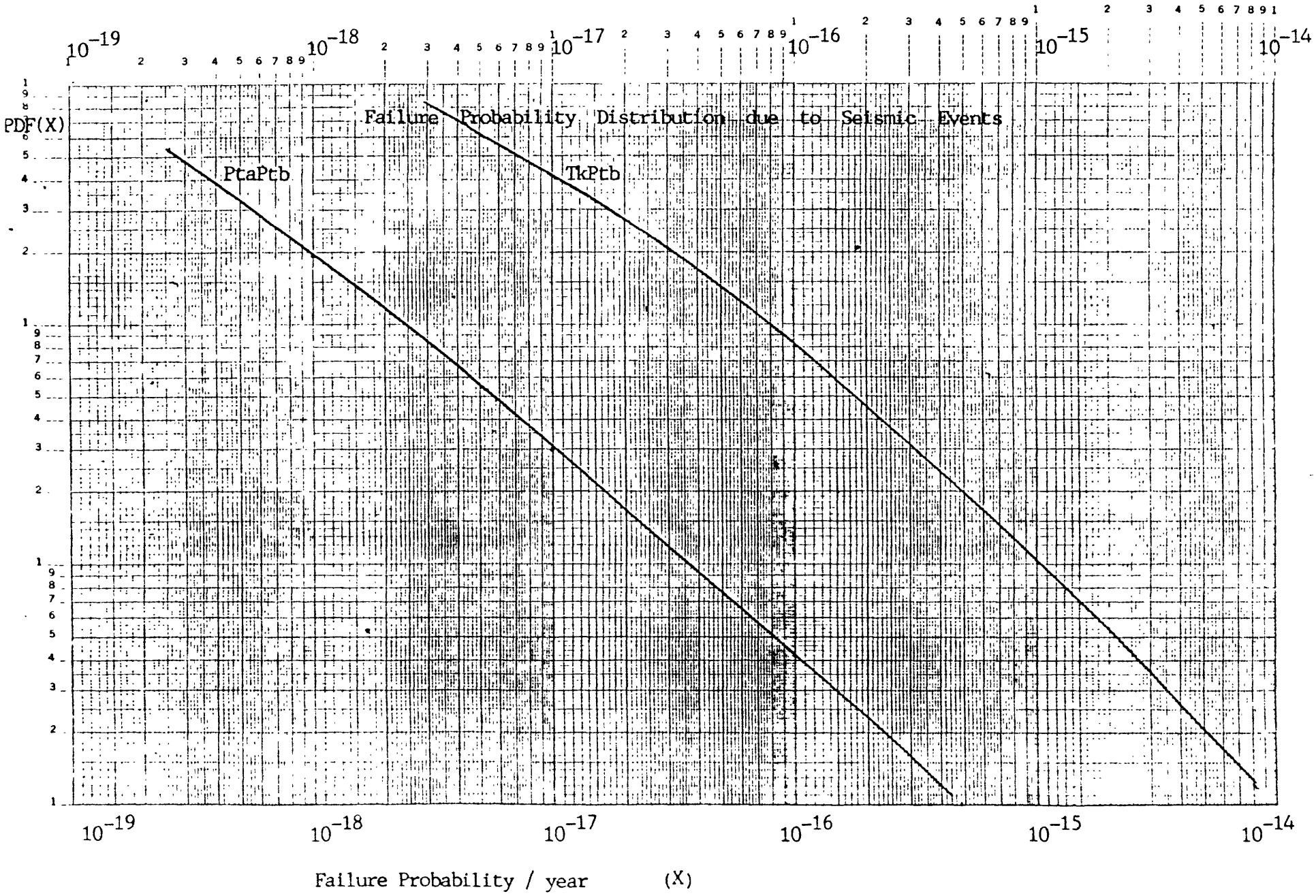
K+E LOGARITHMIC 3 x 5 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 7522

Figure 24, cont'd...



K+E LOGARITHMIC 3 x 5 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 7522

Figure 24, cont'd...



of 1.85×10^{-5} (mean $\hat{\mu} - 2.3 \times 10^{-5}$, $\sigma^2 = 2.97 \times 10^{-10}$), S2 a median of 5.25×10^{-8} (mean $\mu = 1.01 \times 10^{-7}$, $\sigma^2 = 2.77 \times 10^{-14}$) and S3 a median of 6.61×10^{-7} (mean $\mu = 3.27 \times 10^{-6}$, $\sigma^2 = 2.529 \times 10^{-10}$). Results of the DPD code output are shown in Tables XXII - XXIV.

D. Comparison of DPD Uncertainty Treatment with Method-of-Moments

Two methods were used to compute the overall system failure probability due to seismic events. One was to take each cutset's individual fragility function and combine it, using DPD arithmatic, with the seismicity curve and then combine each of these distributions together, and the other was to first combine all the cutset fragility curves together, using the Method-of-Moments to obtain the system fragility curves (see Figure 25), and then combine this with the seismicity curves to obtain the overall system failure probability due to seismic events. Results showed a small discrepancy in the values computed for the mean and variance of the final system failure probability (TABLE XXV) between the two approaches.*

V. Summary/Conclusions

The MOBB code was extended to include uncertainty on the calculation of individual cutset unavailabilities using both Monte Carlo and Method-of-Moments methods. The Method-of-Moments was found most efficient and was implemented in the final code version. A second method for computing system unavailability due to common causes was developed employing the concepts used most often in nuclear risk assessments for external event analysis, particularly for seismic risk. Both approaches must be further tested and compared before a

*This indicates that either approach is equally suitable.

TABLE XXII

Results of DPD Code on FPS Problem

S1

MEDIAN=	1.8500E-05
LOG STD=	.66611
MEAN=	2.3095E-05
VARIANCE=	2.9788E-10
MODE=	1.1871E-05

PDF(X)	CDF(X)	X
10653.	1.0749E-02	4.0000E-06
13120.	1.5149E-02	4.3705E-06
15875.	2.1017E-02	4.7752E-06
18872.	2.8702E-02	5.2175E-06
22042.	3.8593E-02	5.7007E-06
25293	5.1100E-02	6.2287E-06
28515.	6.6638E-02	6.8055E-06
31584.	8.5603E-02	7.4358E-06
34370.	.10835	8.1245E-06
36746.	.13514	8.8769E-06
38598.	.16617	9.6990E-06
39833.	.20145	1.0597E-05
40387.	.24088	1.1579E-05
40231.	.28417	1.2651E-05
39373.	.33086	1.3823E-05
37858.	.38035	1.5103E-05
35763.	.43188	1.6502E-05
33193.	.48459	1.8030E-05
30267.	.53758	1.9700E-05
27115.	.58991	2.1524E-05
23866.	.64068	2.3518E-05
20638.	.68908	2.5696E-05
17534.	.73442	2.8076E-05
14635.	.77613	3.0676E-05
12002.	.81385	3.3517E-05
9670.1	.84735	3.6621E-05
7654.6	.87659	4.0013E-05
5953.0	.90166	4.3719E-05
4548.5	.92278	4.7768E-05
3414.5	.94027	5.2192E-05
2518.3	.95449	5.7025E-05

TABLE XXIII

Results of DPD Code on FPS Problem

MEDIAN=	5.2500E-08
LOG STD=	1.1451
MEAN=	1.0113E-07
VARIANCE=	2.7726E-14
MODE=	1.4148E-08

PDF(X)	CDF(X)	X
1.0022E+05	1.0252E-05	4.0000E-10
1.8222E+05	2.4438E-05	5.0197E-10
3.1855E+05	5.6088E-05	6.2994E-10
5.3539E+05	1.2404E-04	7.9053E-10
8.6510E+05	2.6423E-04	9.9205E-10
1.3440E+06	5.4231E-04	1.2450E-09
2.0075E+06	1.0729E-03	1.5623E-09
2.8830E+06	2.0460E-03	1.9606E-09
3.9804E+06	3.7624E-03	2.4604E-09
5.2838E+06	6.6735E-03	3.0876E-09
6.7436E+06	1.1421E-02	3.8748E-09
8.2748E+06	1.8866E-02	4.8626E-09
9.7619E+06	3.0090E-02	6.1021E-09
1.1072E+07	4.6366E-02	7.6578E-09
1.2075E+07	6.9057E-02	9.6100E-09
1.2660E+07	9.9476E-02	1.2060E-08
1.2761E+07	.13868	1.5134E-08
1.2368E+07	.18729	1.8992E-08
1.1524E+07	.24521	2.3834E-08
1.0324E+07	.31159	2.9910E-08
8.8918E+06	.38475	3.7534E-08
7.3632E+06	.46227	4.7103E-08
5.8623E+06	.54125	5.9111E-08
4.4874E+06	.61863	7.4179E-08
3.3025E+06	.69153	9.3090E-08
2.3367E+06	.75756	1.1682E-07
1.5896E+06	.81508	1.4660E-07
1.0397E+06	.86326	1.8397E-07
6.5379E+05	.90206	2.3087E-07
3.9527E+05	.93211	2.8973E-07
2.2975E+05	.95449	3.6359E-07

TABLE XXIV

Results of DPD Code on FPS Problem

S3

MEDIAN=	6.6181E-07
LOG STD=	1.7889
MEAN=	3.2782E-06
VARIANCE=	2.5294E-10
MODE=	2.6972E-08

PDF(X)	CDF(X)	X
3.0611E+05	1.4129E-04	1.0000E-09
4.0491E+05	2.5830E-04	1.3283E-09
5.2227E+05	4.6101E-04	1.7644E-09
6.5689E+05	8.0359E-04	2.3437E-09
8.0567E+05	1.3682E-03	3.1131E-09
9.6355E+05	2.2756E-03	4.1352E-09
1.1237E+06	3.6978E-03	5.4928E-09
1.2779E+06	5.8715E-03	7.2962E-09
1.4171E+06	9.1110E-03	9.6916E-09
1.5324E+06	1.3820E-02	1.2873E-08
1.6159E+06	2.0493E-02	1.7100E-08
1.6615E+06	2.9717E-02	2.2714E-08
1.6659E+06	4.2151E-02	3.0171E-08
1.6288E+06	5.8494E-02	4.0077E-08
1.5529E+06	7.9441E-02	5.3234E-08
1.4437E+06	.10562	7.0711E-08
1.3088E+06	.13754	9.3926E-08
1.1570E+06	.17548	1.2476E-07
9.9734E+05	.21946	1.6572E-07
8.3835E+05	.26917	2.2013E-07
6.8718E+05	.32397	2.9240E-07
5.4925E+05	.38288	3.8840E-07
4.2809E+05	.44464	5.1591E-07
3.2536E+05	.50778	6.8529E-07
2.4113E+05	.57072	9.1028E-07
1.7426E+05	.63190	1.2091E-06
1.2280E+05	.68991	1.6061E-06
84389.	.74354	2.1334E-06
56548.	.79189	2.8338E-06
36950.	.83440	3.7642E-06
23544.	.87085	5.0000E-06

Figure 25

Method-of-Moments Used to Combine Cutset Fragility Curves

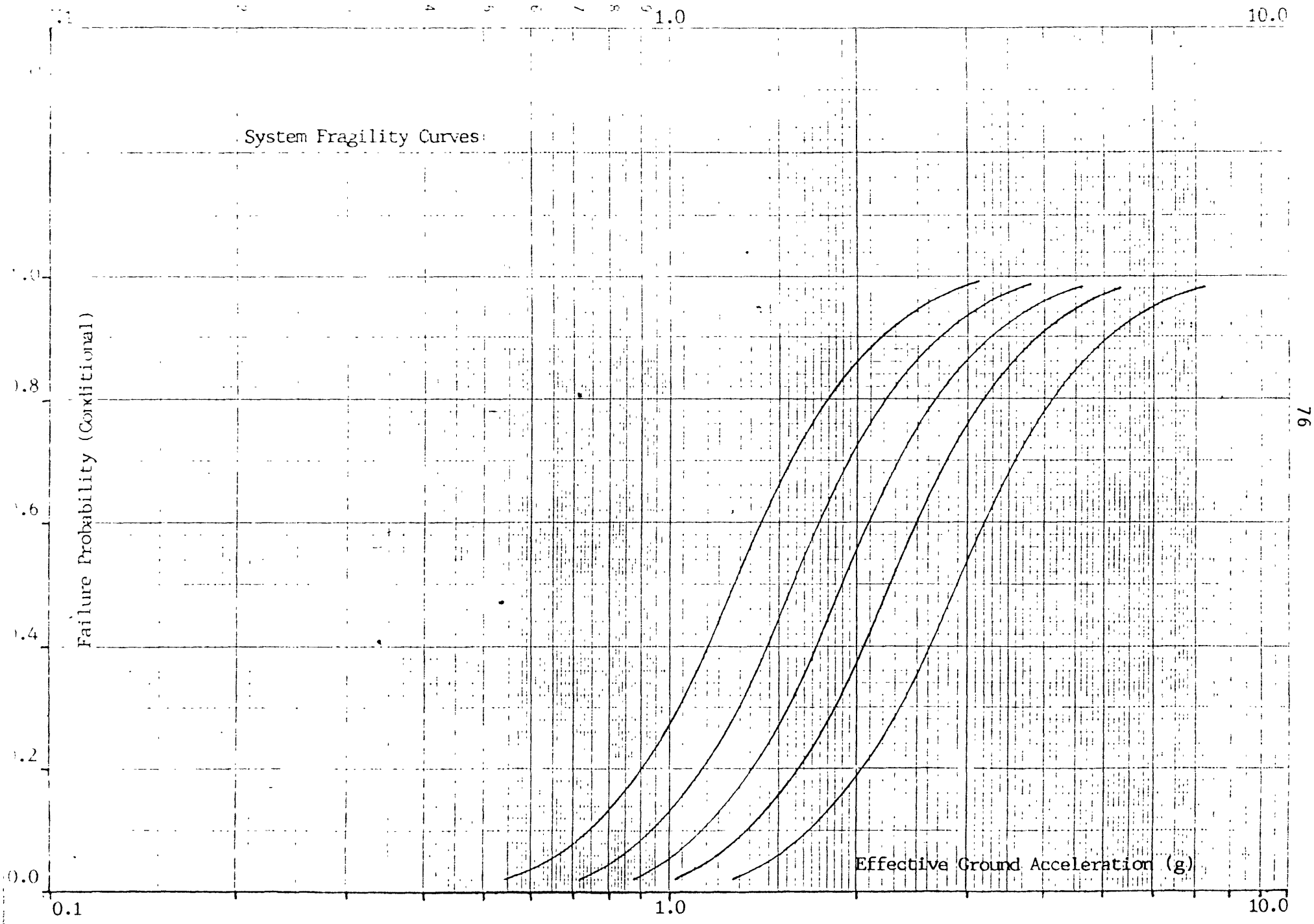


TABLE XXV

COMPARISON OF APPROACHES FOR COMBINING CUTSET FRAGILITY (SUSCEPTIBILITY) CURVES

Method 1:

- Established seismic frequency curves
- Specified components' fragility functions
- Compute components' failure probability distribution functions (DPD)
- Compute system failure probability distribution using the DPD method

Mean = 1.52×10^{-7}/yr

Var = 2.09×10^{-14}

Mean to standard deviation ratio = 1.0514

Method 2:

- Seismicity curves
- Components' fragility functions
- Use the Method-of-Moments to find the system fragility functions
- Compute system unavailability distribution function (DPD)

Mean = 7.14×10^{-8}/yr

Var = 5.09×10^{-15}

Mean to standard deviation ratio = 1.0008

recommendation can be made as to which is preferable. Simple problems demonstrating the use of each approach were made, but work must be done to gather further experience on more realistic, large utility systems before firm conclusions can be drawn on the final usefulness of each approach.

A follow-up project has been proposed (see Appendix F.4) to accomplish these goals.

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APPENDIX A: Mathematical Formula

A.1 The Method of Moments

The method of moments is one of the methods to propagate uncertainty by calculate the moments of the system distribution from the moments of the component distributions. The equations of evaluating the moments of the system distribution can be derived from the multivariated Taylor series expansion of the system function.

Let the system function F, which has n independent variables $X_1, X_2, \ldots X_n$

$$F = f(X_1, X_2, \ldots X_n) \tag{A1}$$

The Taylor series expansion of the function F about the mean values $\bar{X}_1, \bar{X}_2, \ldots \bar{X}_n$

$$\begin{aligned} F = {} & f(\bar{X}_1, \bar{X}_2, \ldots \bar{X}_n) + \\ & (X_1-\bar{X}_1)\frac{\delta f}{\delta X_1} + (X_2-\bar{X}_2)\frac{\delta f}{\delta X_2} + \ldots + (X_n-\bar{X}_n)\frac{\delta f}{\delta X_n} + \\ & \frac{1}{2!}[\,(X_1-\bar{X}_1)^2\frac{\delta^2 f}{\delta X_1^2} + (X_2-\bar{X}_2)^2\frac{\delta^2 f}{\delta X_2^2} + \ldots + (X_n-\bar{X}_n)^2\frac{\delta^2 f}{\delta X_n^2} + \\ & 2(X_1-\bar{X}_1)(X_2-\bar{X}_2)\frac{\delta^2 f}{\delta X_1 \delta X_2} + \ldots\,] + \frac{1}{3}[\,(X_1-\bar{X}_1)^3\frac{\delta^3 f}{\delta X_1^3} + \ldots\,] + \ldots \\ = {} & f(\bar{X}_1, \bar{X}_2, \ldots \bar{X}_n) + \sum_{i=1}^{n}\frac{\delta f}{\delta X_i}(X_i-\bar{X}_i) + \\ & \frac{1}{2}\,[\,\sum_{i=1}^{n}\frac{\delta^2 f}{\delta X_i^2}(X_i-\bar{X}_i)^2 + 2\sum_{i=1}^{n-1}\sum_{j=i-1}^{n}\frac{\delta^2 f}{\delta X_i \delta X_j}(X_i-\bar{X}_i)(X_j-\bar{X}_j)\,] + \ldots \end{aligned} \tag{A2}$$

with all derivatives evaluated at the point $(\bar{X}_1, \bar{X}_2, \ldots, \bar{X}_n)$.

The Taylor expansion for n independent variables can be written in symbolic form

$$f(X_j) = \sum_{m=0}^{\infty} \frac{t^m}{m!} \left[\sum_{i=1}^{n} \alpha_i \frac{\delta}{\delta X_i} \right]^m f(X_k) \Big|_{X_k=\bar{X}_k} \tag{A3}$$

where $\alpha_i = (X_i - \bar{X}_i)$

A convenient vector form is:

$$\psi(\underline{r} + \underline{a}) = \sum_{m=0}^{\infty} \frac{1}{n!} (\underline{a} \cdot \nabla)^m \psi(\underline{r}) \tag{A4}$$

The mean of F is the expectation value of F

$$E[F] = f(\bar{X}_1, \bar{X}_2, \ldots \bar{X}_n) + \tfrac{1}{2} \sum_{i=1}^{n} \frac{\delta^2 f}{\delta X_i^2} E[(X_i - \bar{X}_i)]^2$$
$$+ \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{\delta^2 f}{\delta X_j \delta X_i} E[(X_i - \bar{X}_i)(X_j - \bar{X}_j)] + \ldots \tag{A5}$$

The variance $\mathrm{var}(X_i) = E[(X_i - \bar{X}_i)]^2 = E[X_i^2] - E[X_i]^2$ (A6)

The covariance $\mathrm{cov}(X_i, X_j) = E[(X_i - \bar{X}_i)(X_j - \bar{X}_j)]$ (A6)

$$= \rho_{ij} [\mathrm{var}(X_i)\ \mathrm{var}(X_j)]$$

where ρ_{ij} is the correlation coefficient of X_i and X_j

$$-1 \leq \rho_{ij} \leq 1$$

If X_i and X_j is uncorrelated $\rho_{ij} = 0$ and $\mathrm{cov}(X_i, X_j) = 0$

The variance of F is the second moment about the mean:

$$\mathrm{var}(F) = E[F^2] - (E[F])^2$$

$$= \sum_{i=1}^{n} \left(\frac{\delta f}{\delta X_i} \right)^2 \mathrm{var}(X_i) + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{\delta^2 f}{\delta X_i \delta X_j} \mathrm{cov}(X_i, X_j) + \cdots \quad \text{(A7)}$$

When fault tree method is used for analyzing system failure probability the system equation is often expressed in sum of product form. Two special cases where F is either the sum or the product of its component distributions.

Case 1

$$F = f(X_1, X_2, \ldots X_n)$$

$$= \sum_{i=1}^{n} X_i \quad \text{(A8)}$$

Mean

$$E[F] = \sum_{i=1}^{n} \overline{X}_i \quad \text{(A9)}$$

Variance

$$\mathrm{var}(F) = \sum_{i=1}^{n} \mathrm{var}(X_i) + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{cov}(X_i, X_j) \quad \text{(A10)}$$

Case 2

$$F = f(X_1, X_2, \ldots X_n)$$

$$= \prod_{i=1}^{n} X_i \quad \text{(A11)}$$

Mean

$$E[F] = \prod_{i=1}^{n} \bar{X}_i + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{\hat{X}}{\bar{X}_i \bar{X}_j} \operatorname{cov}(X_i, X_j) \tag{A12}$$

Variance

$$\begin{aligned} \operatorname{var}(F) = & \sum_{i=1}^{n} \left[\frac{\hat{X}}{\bar{X}_i} \right]^2 \operatorname{var}(X_i) \\ & + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \left[\frac{\hat{X}}{\bar{X}_i \bar{X}_j} \right]^2 E[(X_i - \bar{X}_i)^2 (X_j - \bar{X}_j)^2] \\ & + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{\hat{X}^2}{\bar{X}_i \bar{X}_j} \operatorname{cov}(X_i, X_j) \end{aligned} \tag{A13}$$

where $\hat{X} = \prod_{k=1}^{n} \bar{X}_k$.

For a system consists of two independent nad uncorrelated events X_1 and X_2, the above equations can be written as the following.

Case 1

$$F = X_1 + X_2$$

$$E[F] = \bar{X}_1 + \bar{X}_2 \tag{A14}$$

$$var(F) = var(X_1) + var(X_2) \tag{A15}$$

Caes 2

$$F = X_1 X_2$$

$$E[F] = \bar{X}_1 \bar{X}_2 \tag{A16}$$

$$var(F) = \bar{X}_2^2 var(X_1) + \bar{X}_1^2 var(X_2) + var(X_1) var(X_2) \tag{A17}$$

A.2 The Method of Discrete Probability Distributions [A1]

A discrete probability distribution can be defined by a set of doublets

$$[(p_1,x_1),(p_2,x_2), \ldots ,(p_n,x_n)] \tag{A18}$$

where $x_1,x_2 \ldots x_n$ are the discrete values of the variable x and $p_1,p_2, \ldots ,p_n$ are the probability associated with each x_i. The discrete probability distribution can be written as $[(p_i,x_i)]$ and

$$\sum_{i=1}^{n} P_i = 1 \tag{A19}$$

A.2.1 General Rule of Probability Arithmetic

If $z = f(x,y)$ (A20)

where x and y are independent DPDs

$$x = [(p_i,x_i)]$$

$$y = [(q_j,y_j)]$$

then z is a DPD

$$z = [(r_{ij},z_{ij})] \tag{A21}$$

where $r_{ij} = p_i q_j$

and $z_{ij} = f(x_i,y_j)$

note $\sum_{ij} r_{ij} = 1$

Generalize to the case of more than two arguments in f

$$z = f(x^1,x^2, \ldots, x^M) \tag{A22}$$

where each x^m is a DPD

$$x^m = [(p^m_{i_m},x^m_{i_m})] \tag{A23}$$

Then z is a DPD

$$z = [(r_{i_1 \ldots i_M}, z_{i_1 \ldots i_M})] \tag{A24}$$

where $$r_{i_1 \ldots i_M} = \prod_{m=1}^{M} p_{i_m}^{m} \tag{A25}$$

and $$z_{i_1 \ldots i_M} = f(x_{i_1}^{1}, x_{i_2}^{2}, \ldots, x_{i_M}^{M}) \tag{A26}$$

<u>Probabilistic Addition</u>

$$z = x + y \tag{A27}$$

where $x = [(p_i, x_i)]$

and $y = [(q_j, y_j)]$

and the DPDs x and y are independent, then z is a DPD

$$\begin{aligned} z &= [(r_{ij}, z_{ij})] \\ &= [(p_i q_j, x_i + y_j)] \end{aligned} \tag{A28}$$

<u>Probabilistic Multiplication</u>

$$z = xy \tag{A29}$$

where $x = [(p_i, x_i)]$

and $y = [(q_j, y_j)]$

and the DPDs x and y are independent, then z is a DPD

$$\begin{aligned} z &= [(r_{ij}, z_{ij})] \\ &= [(p_i q_j, x_i y_j)] \end{aligned} \tag{A30}$$

A.2.2 Properties of Probabilistic Operations

Non Distributive

$$x(y+z) \neq xy + xz \tag{A31}$$

Probabilistic multiplication is not distributive because the product DPDs on the right hand of the expression are not independent.

Dependence

When $z = x + x$ or $z = xx$ (A32)

The rule for probabilistic addition is no longer applicable because the independent assumption is not valid in this case. Instead the above expressions can be written as

$$z = 2x \ , \qquad z = x^2 \tag{A33}$$

Condensation Operation

Suppose $z = x + y$, the number of doublets in z is the product of the numbers of doublets of x and y. A condensation operation is used to reduce the number of doublets after each probabilistic operation.

Suppose $(p_i, z_i), (p_{i+1}, z_{i+1}) \ldots (p_I, z_I)$ all lie within a single interval, m. Then these doublets can be aggregated into a new doublet $(\hat{p}_m, \hat{z}_m)$

where $\hat{p}_m = \sum_{j=i}^{I} p_j$ (A34)

$$\hat{z}_m = \frac{1}{\hat{p}_m} \sum_{j=i}^{I} P_j z_j \tag{A35}$$

A.3 Log-Normal Distribution [A2]

Definition

A positive variate x ($0<x<\infty$) such that $y = \log(x)$ is normally distributed with mean μ and variance σ.

$$S_1(x,\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} \cdot \exp[(\log(x)-\mu)^2/(-2\sigma^2)] \qquad x>0$$

$$= 0 \qquad \text{otherwise} \qquad \text{(A36)}$$

The mth moment about the origin

$$= \int_0^1 x^m \, S_1(x,\mu,\sigma)\, dx$$

$$= \exp[m\mu + m^2\sigma^2/2] \qquad \text{(A37)}$$

Mode $= \exp[\mu-\sigma^2]$ (A38)

Median $= \exp[\mu]$ (A39)

Mean $= \exp[\mu + \sigma^2/2]$ (A40)

Variance $= \exp[2\mu + \sigma^2]\{\exp[\sigma^2] - 1]\}$ (A41)

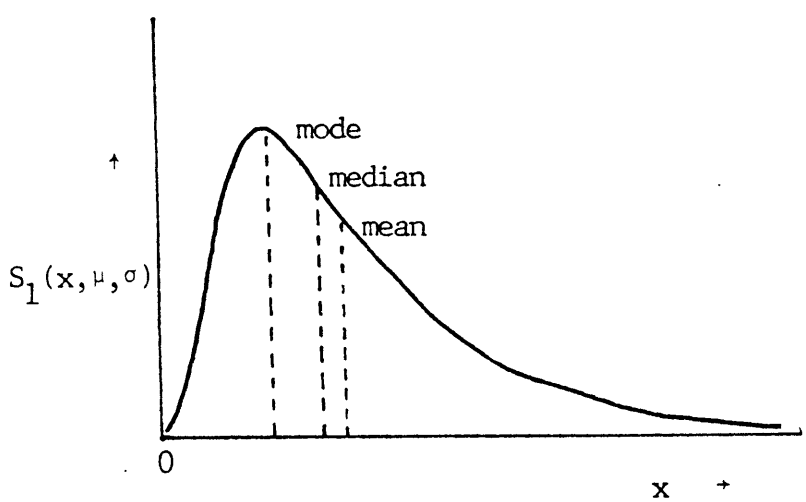


Figure A.1 Frequency Curve of Log-normal Distribution

If ζ_q are the percentiles of order q of $S_1(x,\mu,\sigma)$, ν_q are the percentiles of order q of the normal distribution N(0,1)

$$\zeta_q = \exp[\mu + \nu_q \sigma] \tag{A42}$$

Cumulative Distribution Function

$$\begin{aligned} \mathrm{cdf}[\ S_1(\acute{x},\mu,\sigma)\ ] &= \int_0^{\acute{x}} S_1(x,\mu,\sigma)\ dx \\ &= \tfrac{1}{2}(1 + \mathrm{erf}(z)) \qquad \acute{x} > e^{\mu} \\ &= \tfrac{1}{2}(1 - \mathrm{erf}|z|) \qquad \acute{x} < e^{\mu} \end{aligned} \tag{A43}$$

where $$z = \frac{\log(\acute{x}) - \mu}{\sigma\sqrt{2}}$$

Theorem A.1: Reproductive Property

If X_1 and X_2 are independent log-normal variates, then the product X_1X_2 is $S_1(x|\mu_1+\sigma_2,\ \mu_1+\sigma_2)$. The reproductive property extends to any finite set of independent log-normal variates and also to an infinite sequence provided that some conditions of convergnece are fulfilled.

Theorem A.2: Central Limit Theorem

If $[X_j]$ is a sequence of independent, positive variates having the same probability distribution and such that

$$E[\log(X_j)] = \mu$$

and $$\mathrm{var}[\log(X_j)] = \sigma^2$$

both exist, then the product $\prod_{j=1}^{n} X_j$ is asymptotically distributed as $S_1(x|\ n\mu\ ,\ n\sigma^2)$.

Estimation of Parameters

There are five types of methods to estimate the parameters and .

i) the method of maximum likelihood,
ii) the method of moments,
iii) the method of quantiles,
iv) the graphical method, and
v) mixed methods.

Suppose there is given a sample S_n of size n consisting observations $x_1, x_2, \ldots, x_n$.

The jth sample moments about the origin is denoted by l'_j.

$$l'_j = \frac{1}{n} \sum_{i=1}^{n} x_i^j \tag{A44}$$

The Method of Maximum Likelihood

The likelihood function of the sample is

$$\frac{1}{\sigma^n (2\pi)^{\frac{1}{2}n} \prod_{i=1}^{n} x_i} \exp\left[- \frac{1}{2\sigma^2} \sum_{i=1}^{n} (\log x_i - \mu)^2 \right] \tag{A45}$$

and the maximum-likelihood estimators m and s of μ and σ are found to be

$$m = \frac{1}{n} \sum_{i=1}^{n} \log x_i \tag{A46}$$

$$s^2 = \frac{1}{n} \sum_{i=1}^{n} (\log x_i - m)^2 \tag{A47}$$

The estimator s is biased but consistent; if, however, the following equation is used

$$s^2 = \frac{1}{n-1} \sum_{i=1}^{n} (\log x_i - m)^2 \tag{A48}$$

then m and s are minimum variance unbiased estimators of μ and σ.

The Graphical Method

The graphical method was discussed in the last section. The estimators m and s can be obtained from the logarithmic probability graph.

The Mixed Method

The estimators m and s are obtained from a combination of different methods discussed above.

Estimates of α and β^2, the mean and variance of the log-normal distribution may be derived from estimates of μ and σ^2 obtained by the methods discussed above.

Example

The DPD of S_2 taken from the sample problem discussed in Chapter 5 are used as sample values in this example. From Figure A.2:

$$x_{16\%} = 1.2 \times 10^{-8}$$

$$x_{50\%} = 4.6 \times 10^{-8}$$

$$x_{84\%} = 1.8 \times 10^{-7}$$

and dervied

$$m = \log(4.6 \times 10^{-8})$$
$$= -9.9869$$

$$s = 1.3541$$

where m and s are the estimators of μ and σ .

The Method of Moments

The estimators m and s of and are obtained by equating the first two sample moments l_1' and l_2' to the expressions

$$l_1' = \exp[m + \tfrac{1}{2}s^2] \tag{A49}$$

$$l_2' = \exp[2m + 2s^2] \tag{A50}$$

whence

$$m = 2\log(l_1') - \tfrac{1}{2}\log(l_2') \tag{A51}$$

and

$$s = \log(l_2') - 2\log(l_1') \tag{A52}$$

The Method of Percentiles

To obtain percentile estimators the sample percentiles of order q_1 and q_2 are set equal to the expressions

$$x_{q1} = \exp[m + \nu_{q1}s] \tag{A53}$$

and

$$x_{q2} = \exp[m + \nu_{q2}s] \tag{A54}$$

so that

$$m = \frac{\nu_{q2}\log(x_{q1}) - \nu_{q1}\log(x_{q2})}{\nu_{q2} - \nu_{q1}} \tag{A54}$$

$$s = \frac{\log(x_{q2}) - \log(x_{q1})}{\nu_{q2} - \nu_{q1}} \tag{A55}$$

Testing for Lognormality and Estimation of Parameters

Testing for Lognormality

Any test of normality may be adapted, by using transformed sample values, as a test of lognormality. In this section only the use of logarithmic probability paper is discussed.

It is a fairly accurate graphical method by the use of logarithmic probability paper. The theory underlying its use is derived from the relation which connects the percentile of order q of $S_1(x| \ , \ )$ and the corresponding percentile of N(0,1)

$$\log(\zeta_q) = \sigma\nu_q + \mu$$

so that the locus of $[\nu_q, \log(\zeta_q)]$ is a straight line.

Although the use of the method can hardly be regarded as a rigorous statistical test of lognormality it nevertheless provides a quick judging whether the population may be lognormal. Moreover, the parameters μ and σ may be estimated from a straight line fitted by eye to the points. The population percentiles of order 16, 50 and 84% are given by

$$\zeta_{16\%} = \exp(\mu - \sigma)$$

$$\zeta_{50\%} = \exp(\mu)$$

and

$$\zeta_{84\%} = \exp(\mu + \sigma)$$

so that

$$\mu = \log(\zeta_{50\%})$$

and

$$\sigma = \log\left[\tfrac{1}{2}\left(\frac{\zeta_{50\%}}{\zeta_{16\%}} + \frac{\zeta_{84\%}}{\zeta_{50\%}}\right)\right]$$

Two advantages of the graphical methods are transformation of sample values is not required and group intervals do not affect the results.

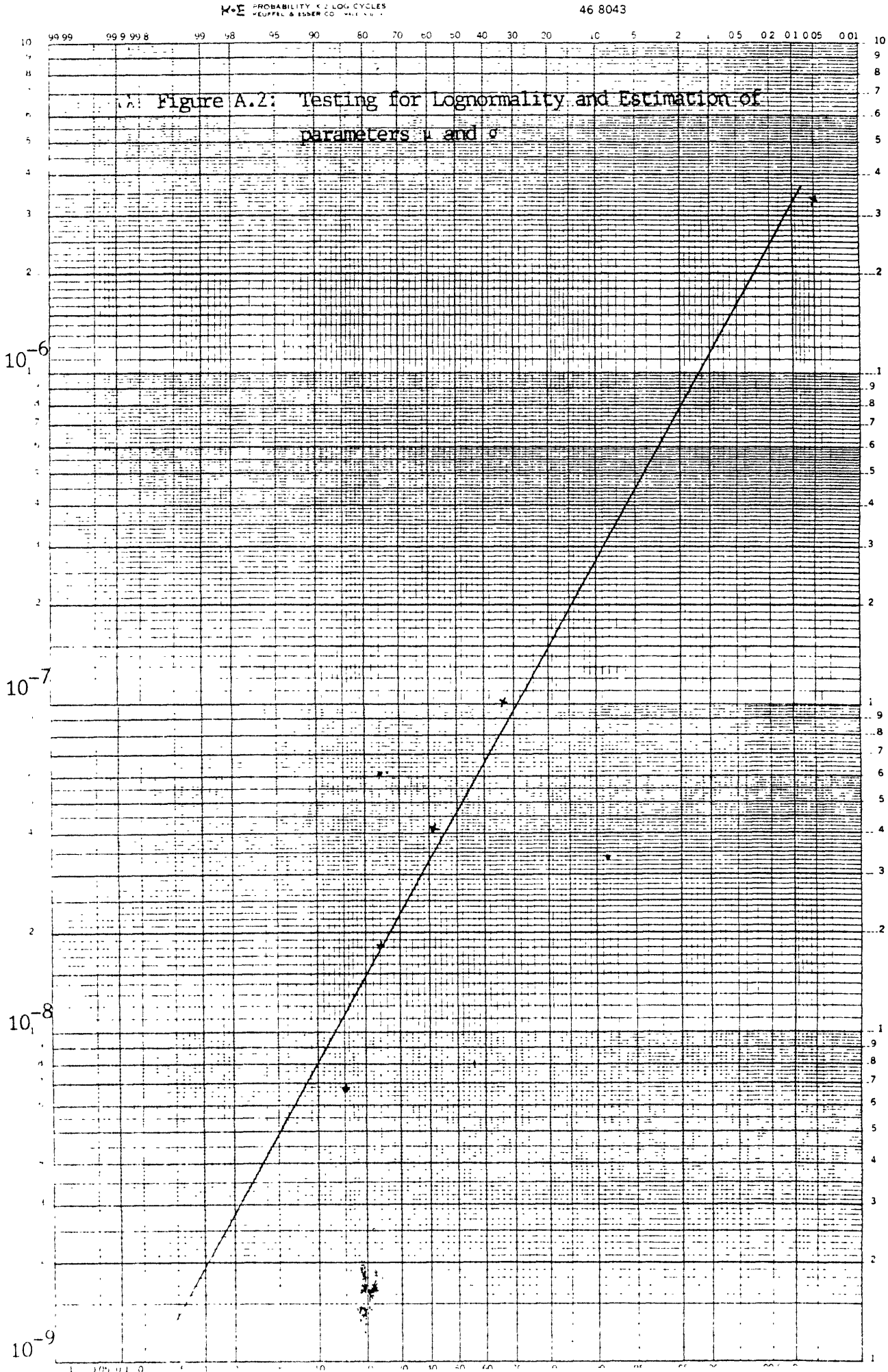


Figure A.2: Testing for Lognormality and Estimation of parameters μ and σ

A.4 Truncated Log-normal Distribution

The truncated log-normal distribution is a special form of the log-normal distribution. The x variate is limited from 0 to 1.

$$S_t(x|\mu,\sigma) = \frac{C}{x\sigma\sqrt{2\pi}} \exp[(\log x - \mu)^2/(2\sigma^2)] \qquad 0 < x < 1$$

$$= 0 \qquad \text{otherwise} \qquad \text{(A56)}$$

where C is the normalization factor

$$C^{-1} = \int_0^1 S_1(x|\mu,\sigma)\, dx \qquad \text{(A57)}$$

the mth moment about the origin

$$= \int_0^1 x^m S_t(x|\mu,\sigma)\, dx \qquad \text{(A58)}$$

<u>Mean</u> $$= \int_0^1 x S_t(x|\mu,\sigma)\, dx \qquad \text{(A59)}$$

<u>Variance</u> $$= E[x^2] - E[x]^2$$

$$= [\int_0^1 x^2 S_t(x|\mu,\sigma)dx] - [\int_0^1 x S_t(x|\mu,\sigma)dx]^2 \qquad \text{(A60)}$$

Unlike the log-normal probability distribution, the mth moment of truncated log-normal probability distribution had to be evaluated numerically. Also there is a discontinuity at x = 0.

$$\lim_{x \to 1^-} S_t(x|\mu,\sigma) = \varepsilon \text{ (non-zero)} \qquad \text{(A61)}$$

$$\lim_{x \to 1^+} S_t(x|\mu,\sigma) = 0 \qquad \text{(A62)}$$

A.5

Bounded Log-normal Probability Distribution [A3]

It is possible to introduce an extension of the log-normal distribution to allow for both a lower and an upper bound to the possible values of the variate. Johnson [A3] had discussed the use of such a distribution. The variate x is confined to the range $\tau < x < \theta$ and

$$x' = \frac{(x - \tau)}{(\theta - x)} \tag{A63}$$

such that x' is log-normally distributed.

The bounded log-normal distribution used in this study is a specialized form of the above distribution. The x variate is confined to the range $0 < x < 1$, that is

$$\tau = 0$$
$$\theta = 1 \tag{A64}$$

The bounded log-normal pdf is defined as the following:

$$S_b(x|\mu,\sigma) = \frac{1}{x(1-x)\sigma\sqrt{2\pi}} \exp-[(\log(\frac{x}{1-x}) - \mu)^2/(2\sigma^2)] \quad 0 < x < 1$$
$$= 0 \qquad \text{otherwise} \tag{A65}$$

Median $$= \frac{\exp(\mu)}{1 + \exp(\mu)} \tag{A66}$$

mth Moment $$= \int_0^1 x^m S_b(x|\mu,\sigma)dx \tag{A67}$$

Mean $$= \int_0^1 x S_b(x|\mu,\sigma)dx \tag{A68}$$

Variance $$= E[(x^2)] - E[(x)]^2 \tag{A69}$$
$$= \int_0^1 x^2 S_b(x|\mu,\sigma)\, dx - [\int_0^1 x S_b(x|\mu,\sigma)dx]^2$$

Percentile of Order q $$\zeta_q = \frac{\exp[\mu + \nu_q\sigma]}{1+\exp[\mu+\sigma\nu_q]} \tag{A70}$$

A.6 The Asymptotic Distribution of the Maximum for Log-normal Distribution [A3,A4]

A distribution which can be obtained as the limit distribution of a properly normalized extreme of independent and identically distributed random variables.

For log-normal distribution, the cdf(x)

$$F(x) = \tfrac{1}{2}\int_{-\infty}^{\log x} \exp[-u^2/2]\, du \qquad x > 0 \qquad (A71)$$

Then the asymptotic distribution of maximum cdf(x) = F*(x)

$$F^*(x) = \exp[-e^{-\alpha(x-\beta)}] \qquad (A72)$$

where $-\infty < x < \infty$,

$\alpha < 0$,

and $-\infty < \beta < \infty$.

The probability density function (pdf)

$$f^*(x) = \frac{\partial F^*(x)}{\partial x} = \alpha\exp[-\alpha(x-\beta)-e^{-\alpha(x-\beta)}] \qquad (A74)$$

The mean value of x and the variance are

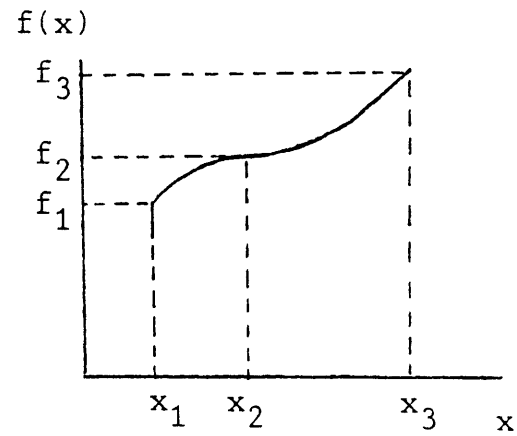
$$m = \beta + .577\alpha^{-1} \qquad (A75)$$

$$\sigma^2 = 1.645\alpha^{-1}$$

A.7 Numerical Integration

NUmerical integration using the Simpson's Rule for the interval $[x_1, x_2]$

$$\int_{x_1}^{x_3} f(x)\, dx$$



$$f(x) = \frac{(x-x_2)\ (x-x_3)}{(x_1-x_2)(x_1-x_3)}\, f_1 + \frac{(x-x_1)\ (x-x_3)}{(x_2-x_1)(x_1-x_3)}\, f_2 + \frac{(x-x_1)\ (x-x_2)}{(x_3-x_1)(x_3-x_2)}\, f_3 \qquad \text{(A76)}$$

$$\int_{x_1}^{x_3} f(x)\, dx = \frac{f_1}{(x_1-x_2)(x_1-x_3)} \int_{x_1}^{x_3} (x^2+x_2x_3-x_2x-x_3x)\, dx + \frac{f_2}{(x_2-x_1)(x_2-x_3)} \int_{x_1}^{x_3} (x^2+x_1x_3-x_1x-x_3x)\, dx + \frac{f_3}{(x_3-x_1)(x_3-x_2)} \int_{x_1}^{x_3} (x^2+x_1x_2-x_1x-x_2x)\, dx$$

$$= \frac{f_1}{3(x_2-x_1)} \left[(x_3+x_1)^2+x_3(3x_2-x_1)-\frac{3}{2}(x_2+x_3)(x_3+x_1)\right] + \frac{(x_3-x_1)^3 f_1}{6(x_2-x_1)(x_3-x_2)} + \frac{f_3}{3(x_3-x_2)} \left[(x_3+x_1)^2+x_1(3x_2-x_3)-\frac{3}{2}(x_1+x_2)(x_3+x_1)\right] \qquad \text{(A77)}$$

When $x_2-x_1 = x_3-x_2 = h$, the familiar Simpson's formula

$$\int_{x_1}^{x_3} f(x)dx = \frac{1}{3} h(f_1+4f_2+f_3) \tag{A78}$$

References

[A1] Kaplan S.,'On the Method of Discrete Probability Distribution and Reliability Calculation - Application to Seismic Risk Assessment', Pickard, Lowe and Garrick, Inc., October 1980.

[A2] Aitchison J. and J. Brown,'The Lognormal Distribution', Monographs 5, University of Cambridge, 1963.

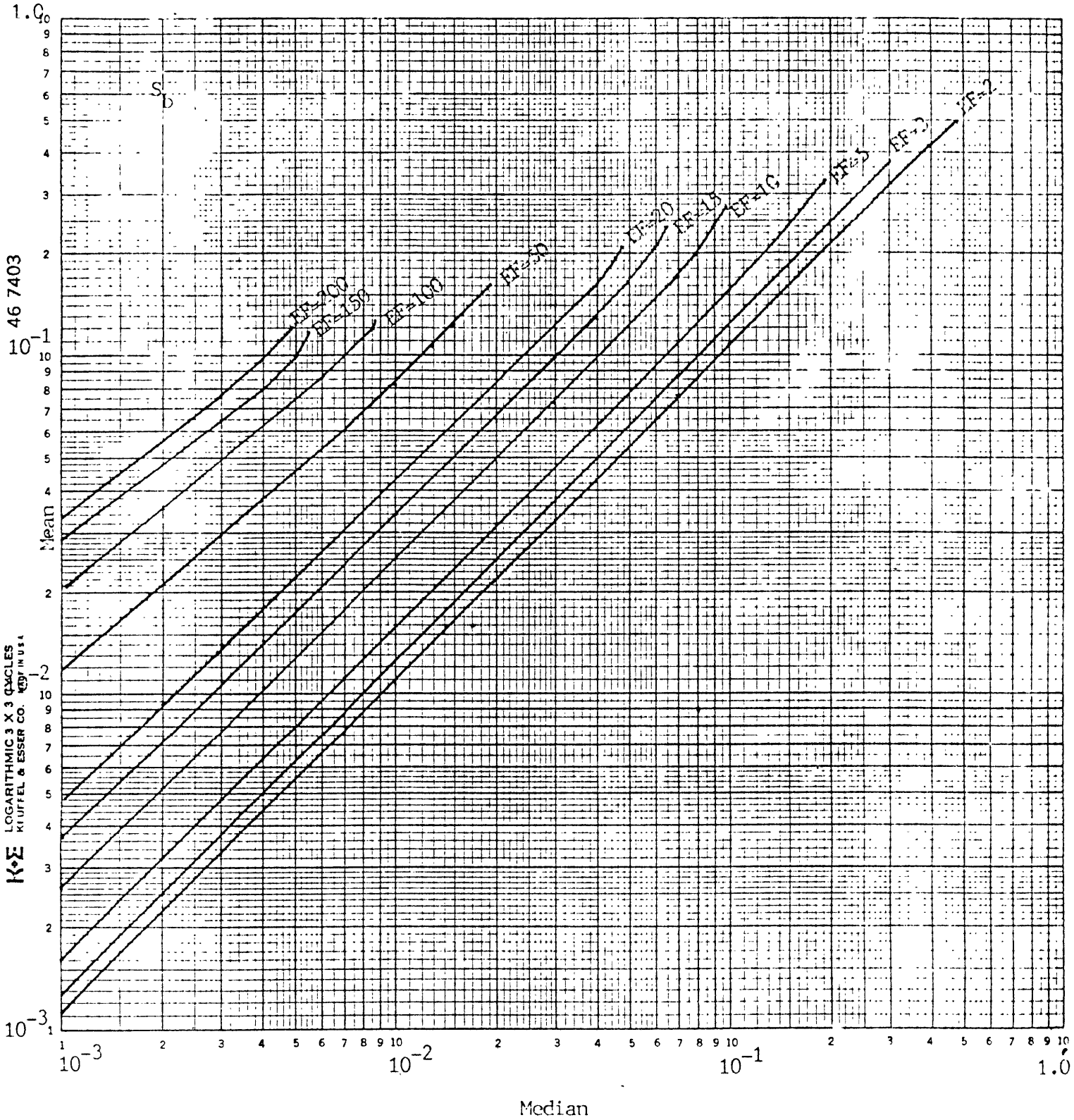
[A3] Galambos J.,'The Asymptotic Theory of Extreme Order Statistics',John Wiley & Sons, 1978.

[A4] Gumbel E.,'Statistics of Extremes',Columbia University Press, New York, 1958.

Appendix B: Figures and Tables of the Moments of S_b, S_l and S_t.

Programme Listings of BORO, LORO and TORO.

Figure B1: The first four moments, variances and $E[(X_i-\bar{X}_i)^4]$ of the bounded log-normal distribution S_b. (19 Sheets)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EF=5
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Mean
Median
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10^{-2}
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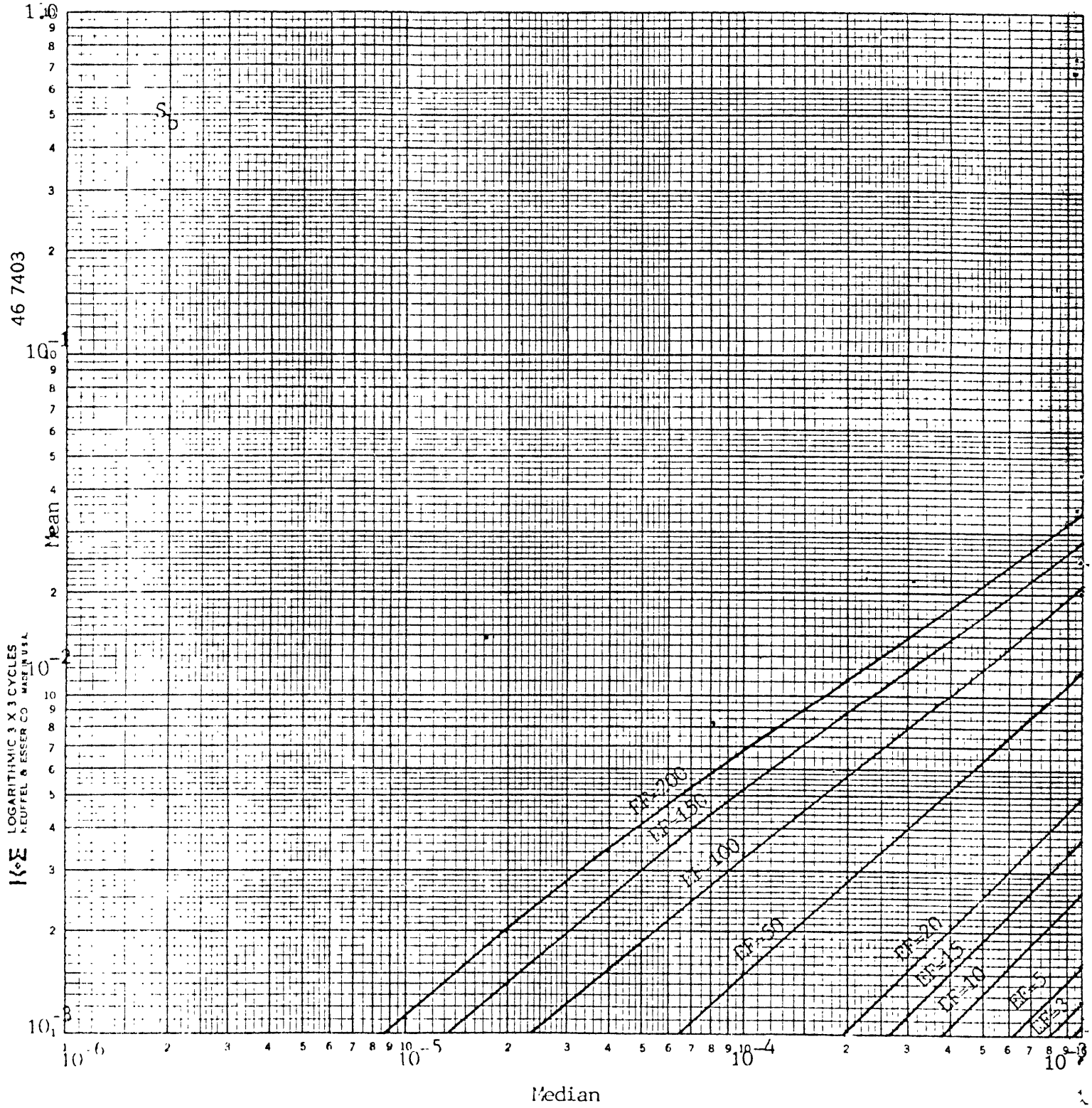
K+E LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.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Mean
Median
LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
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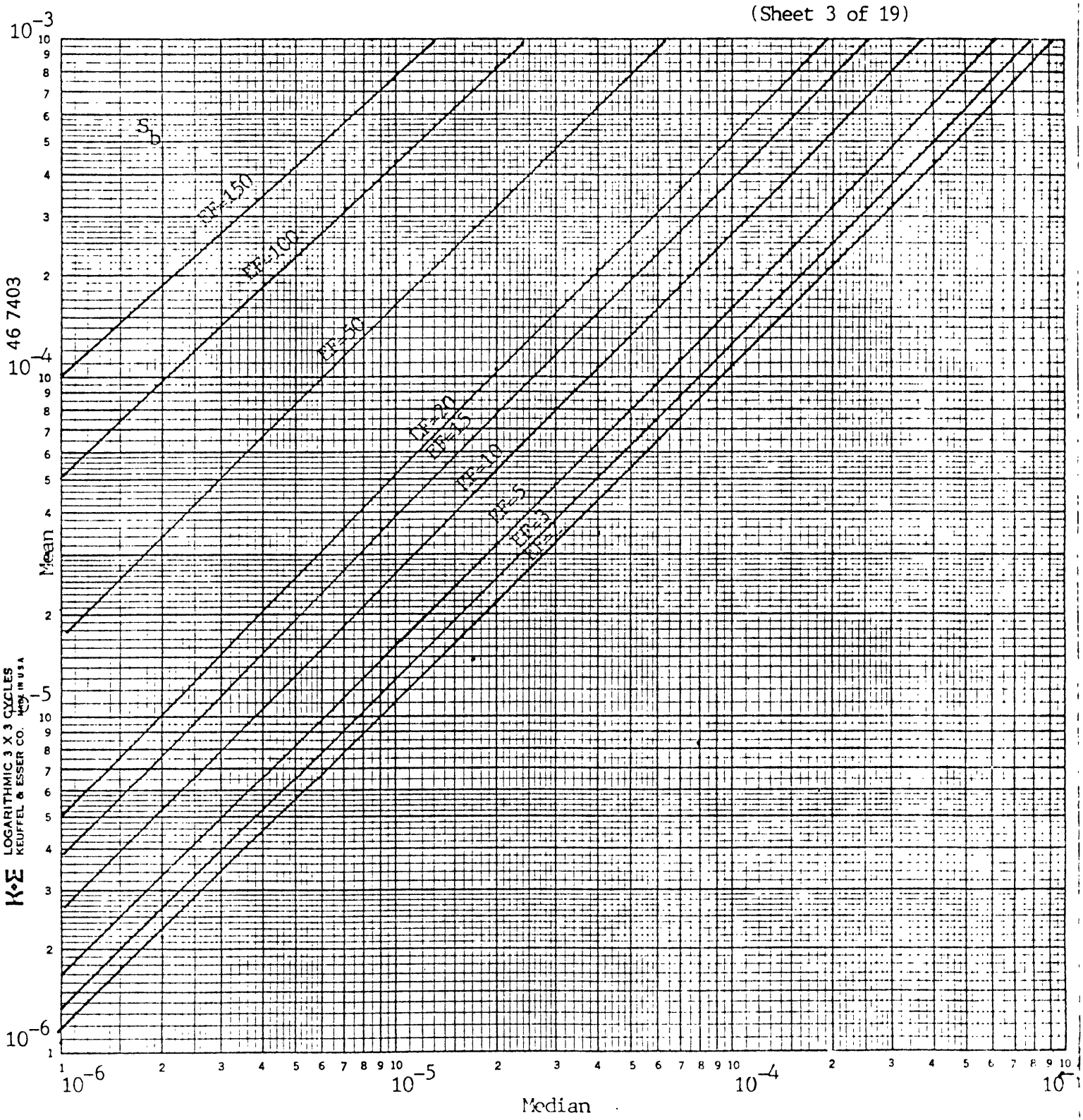
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Mean
Median
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10^{-4}
10^{-5}
10^{-6}
46 7403
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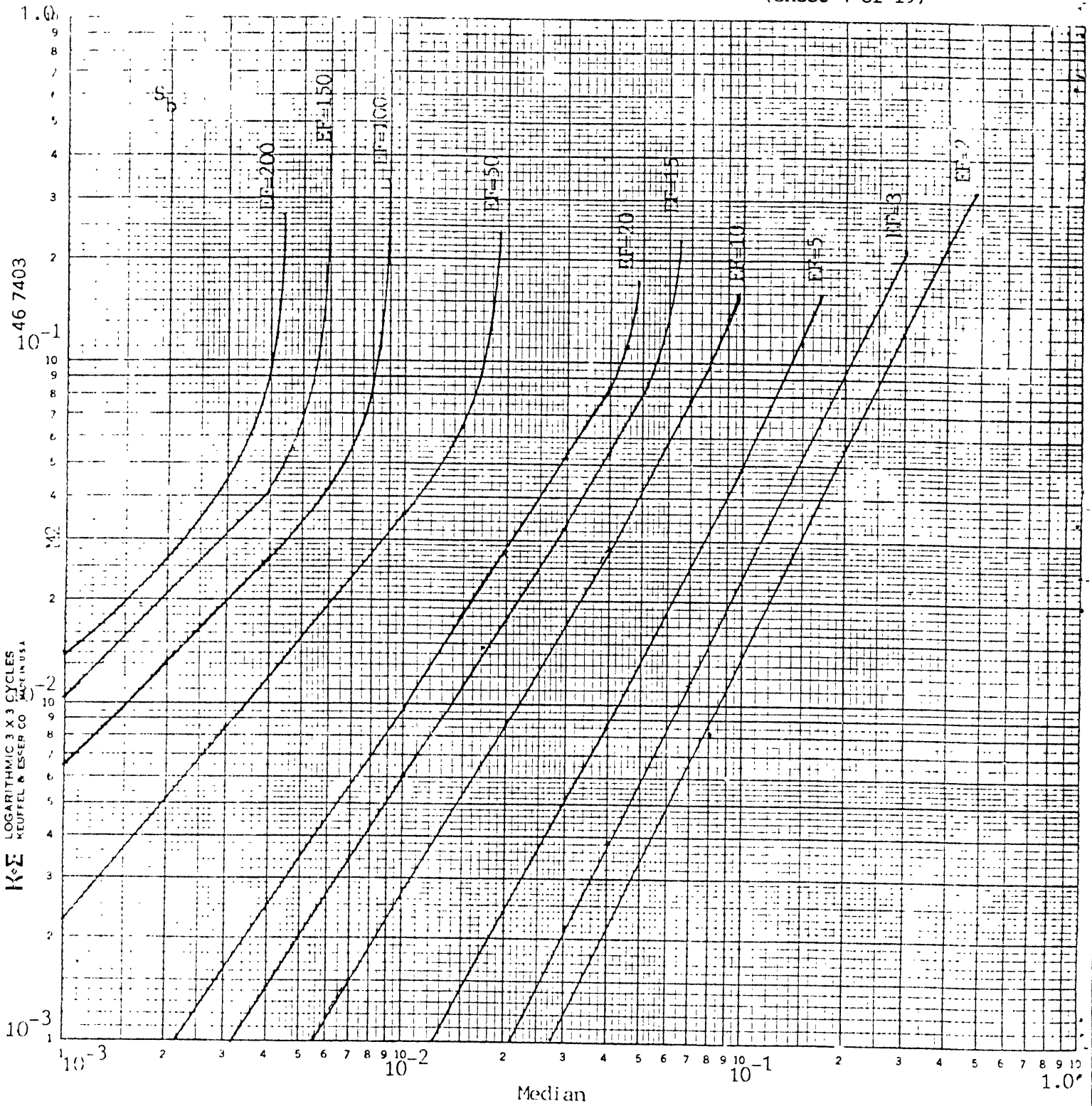
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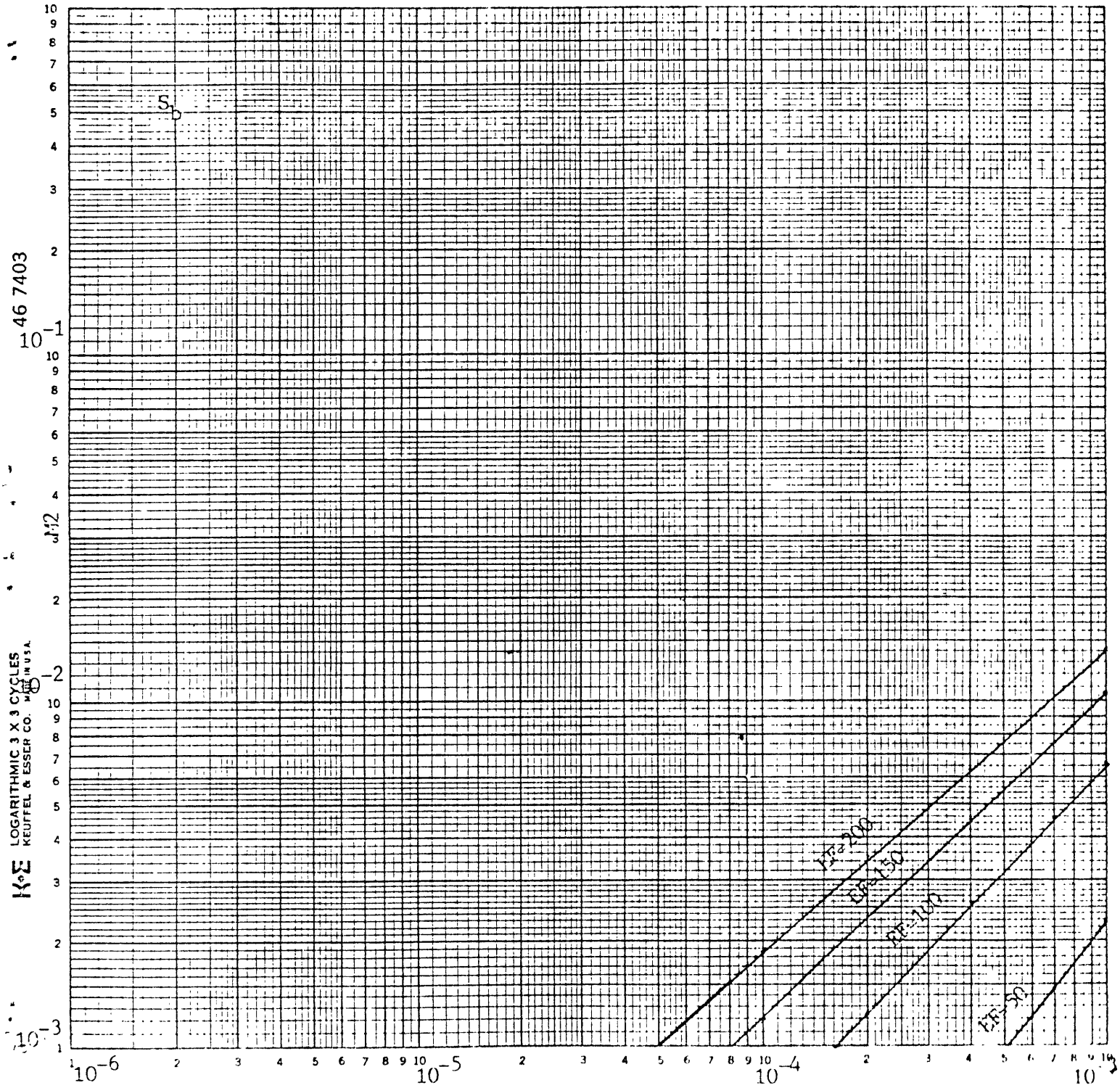
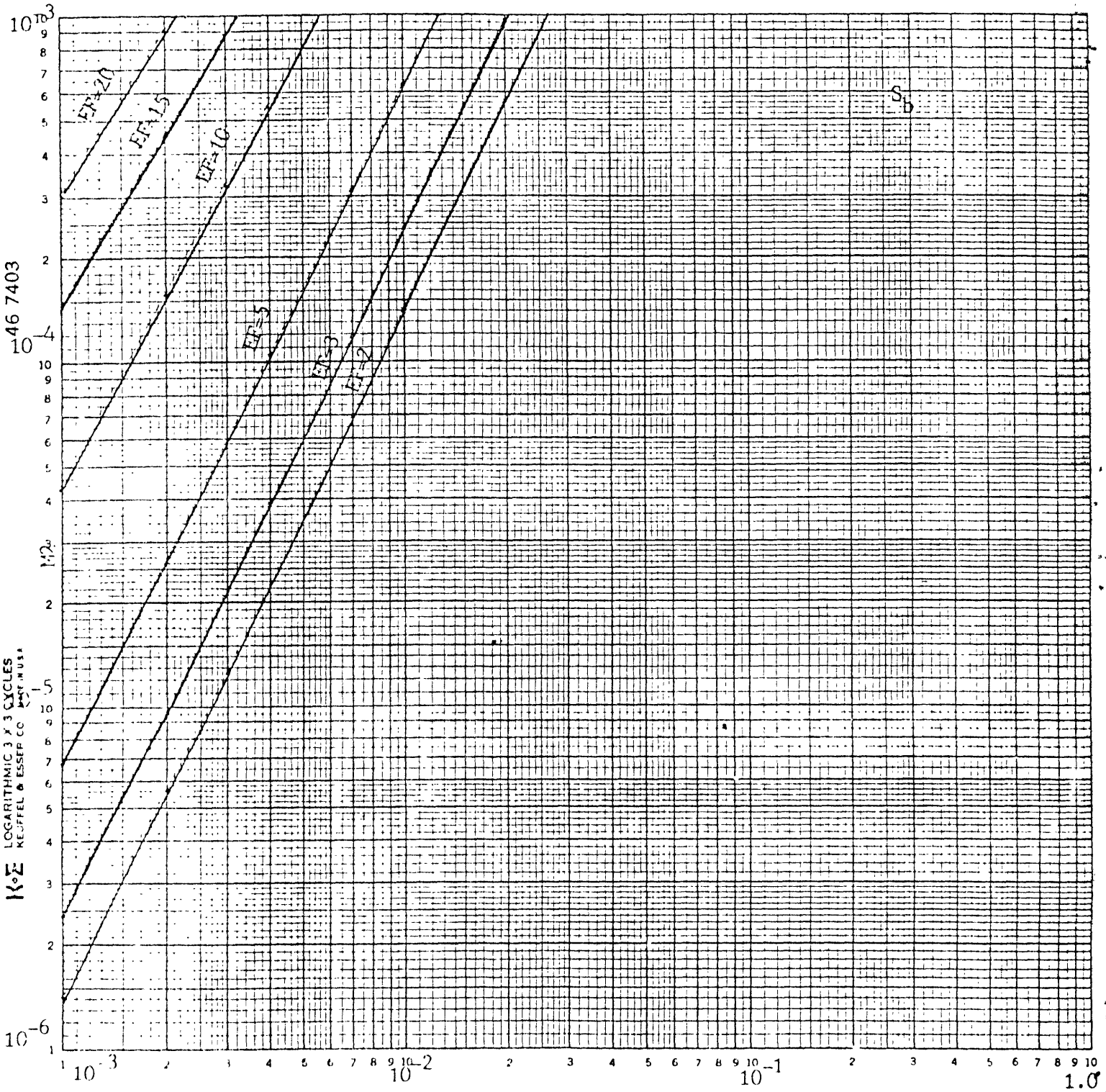
K+E LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
Median

(Sheet 5 of 19)



Median

(Sheet 6 of 19)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10^{-5}
10^{-6}
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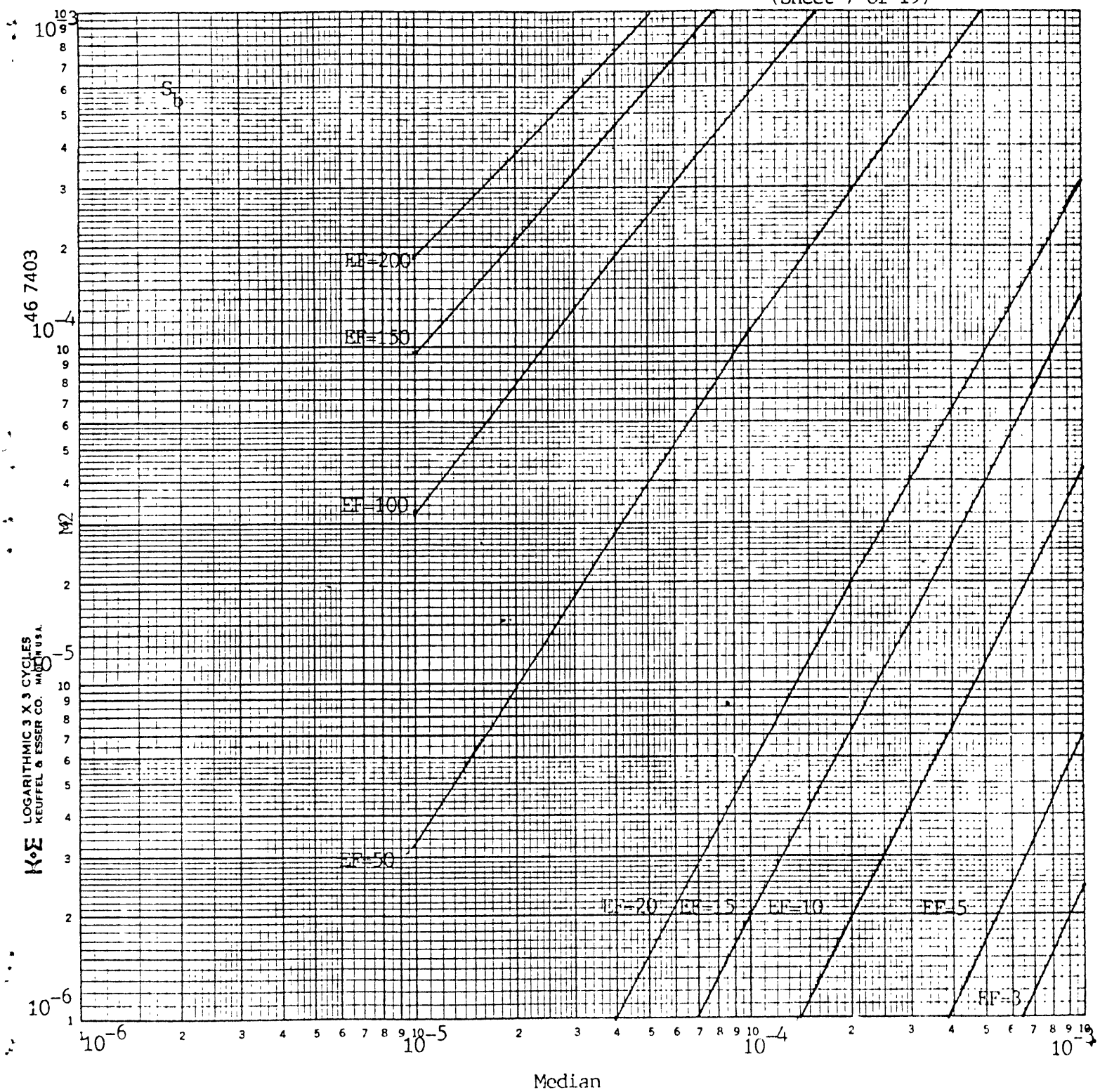
Median
LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO.
46 7403

(Sheet 7 of 19)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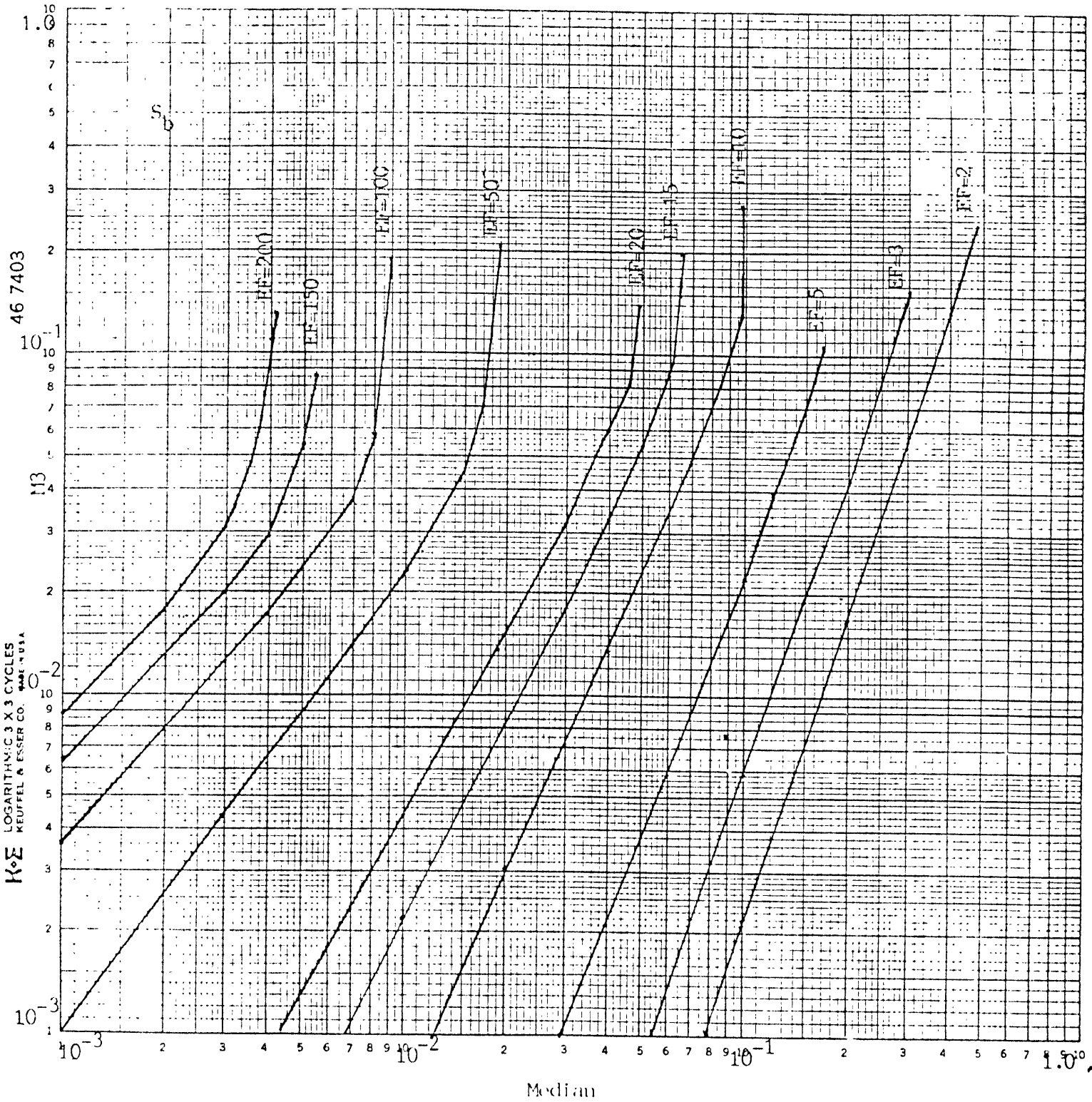
M2
46 7403
K+E LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
10^{-6}
10^{-5}
10^{-4}
10^{-3}
Median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10^{-2}
10^{-3}
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10^{-1}
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Median
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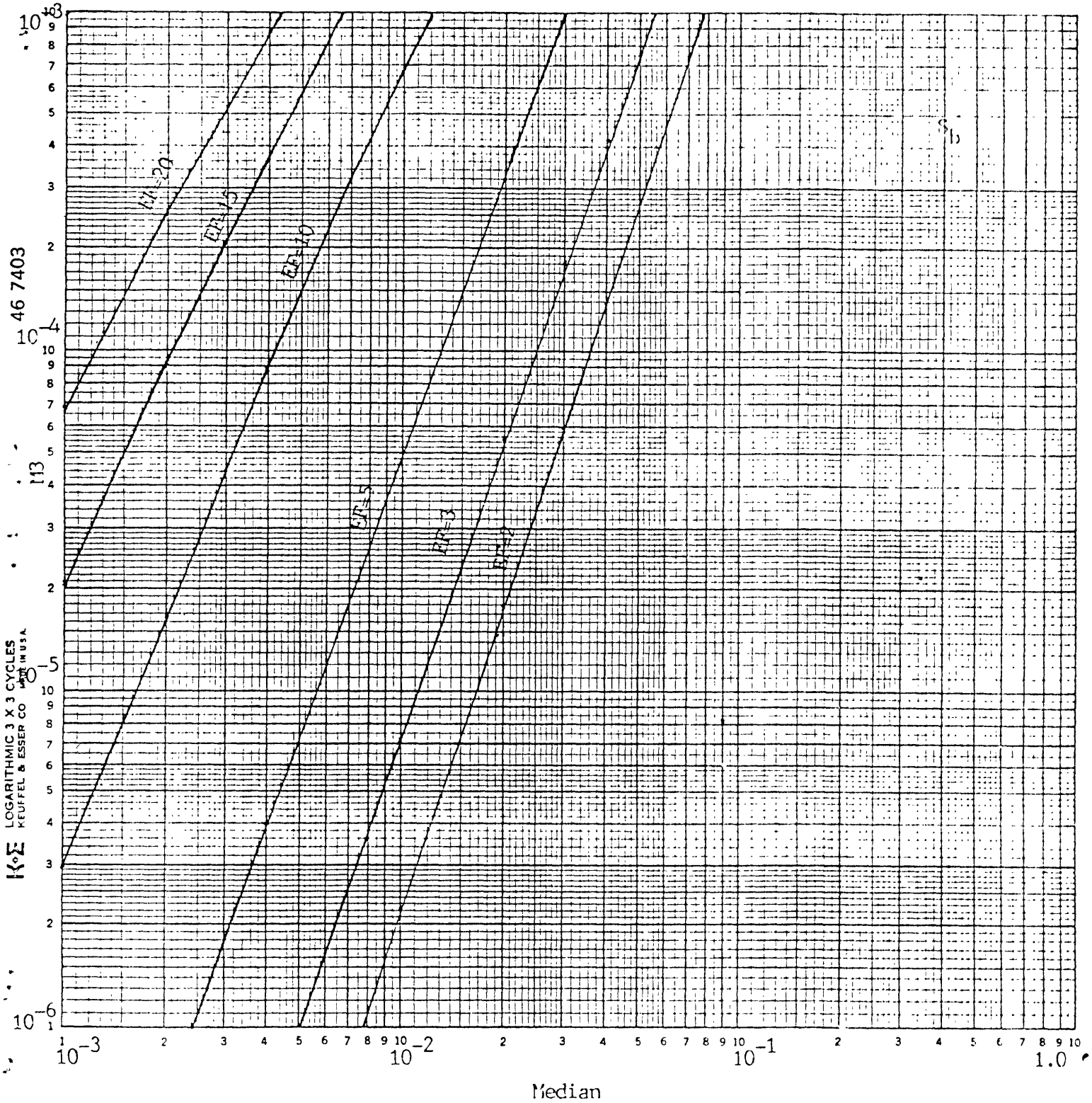
K+E LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO.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10^{-5}
10^{-6}
10^{-3}
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1.0
Median
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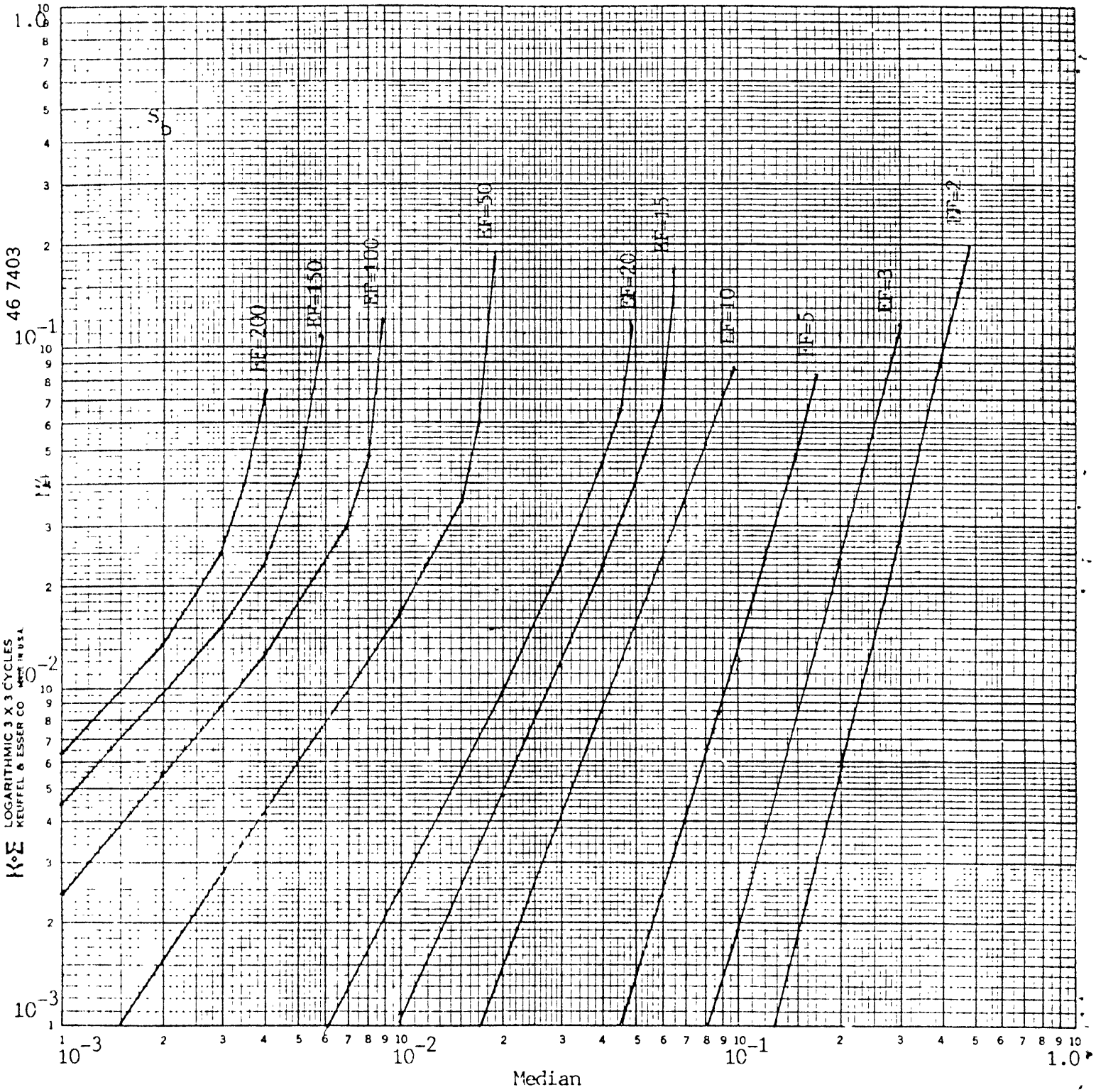
K+E LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.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K+E LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
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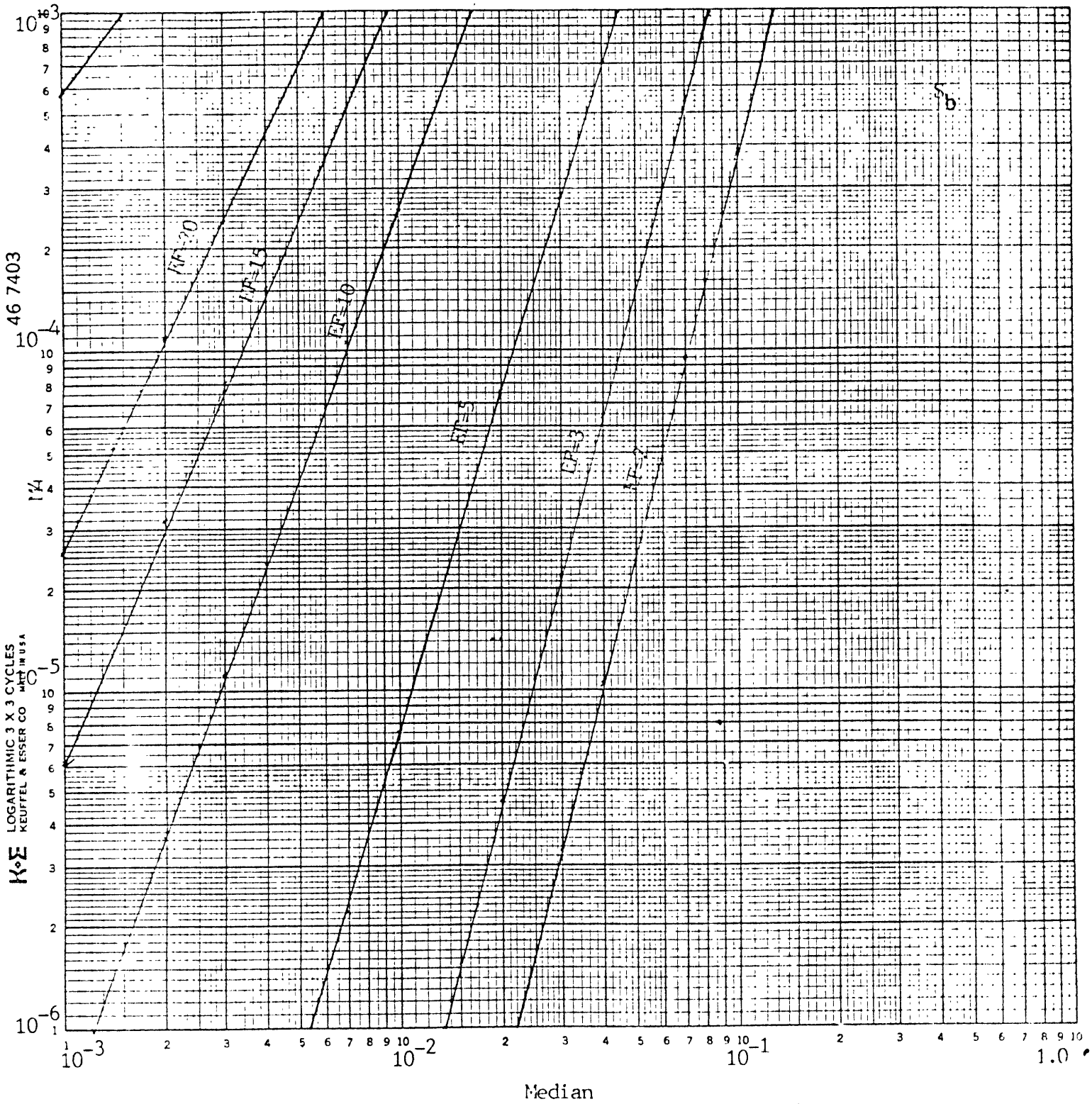
EF=3
EF=2
Median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Median
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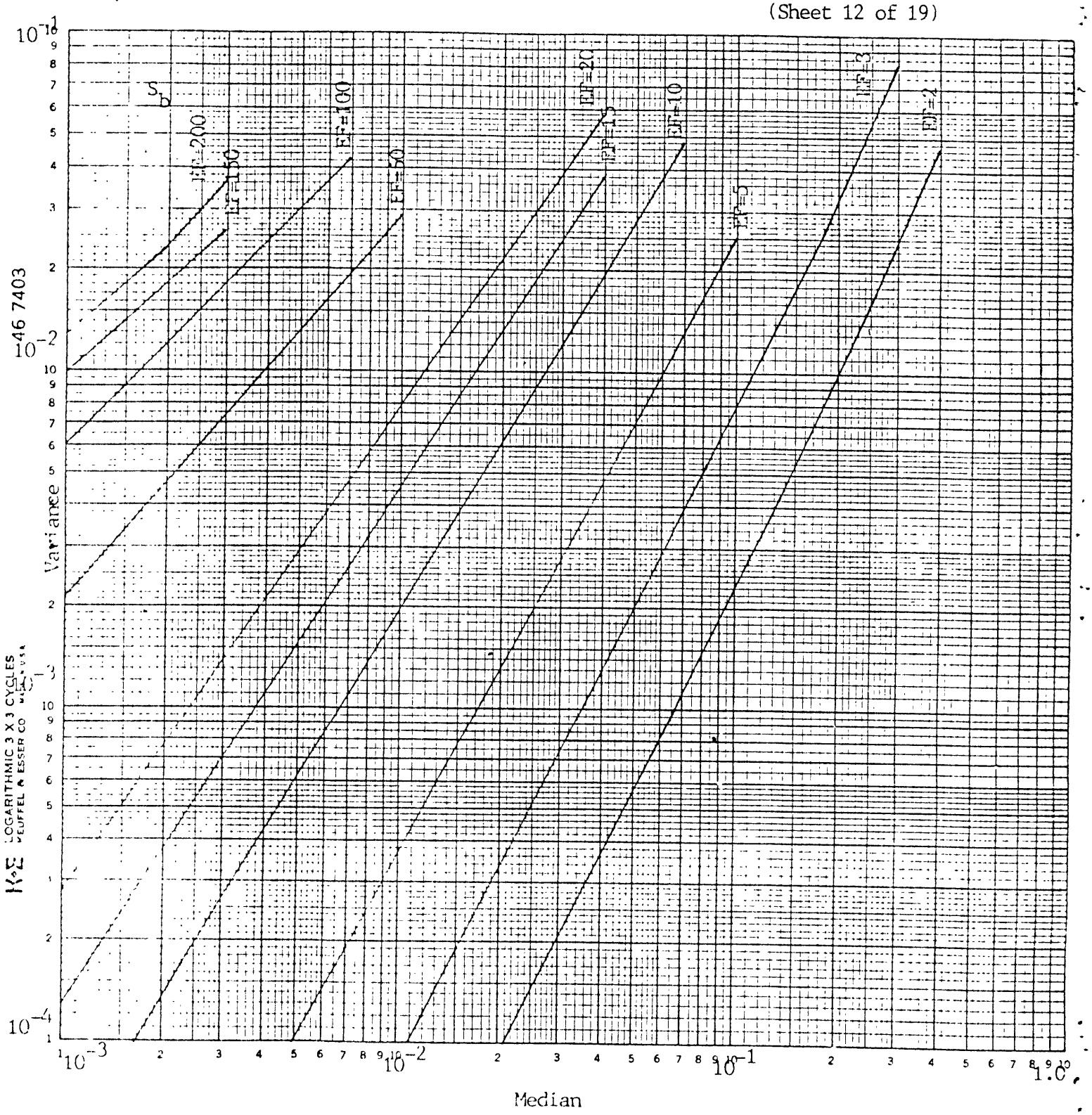
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Median
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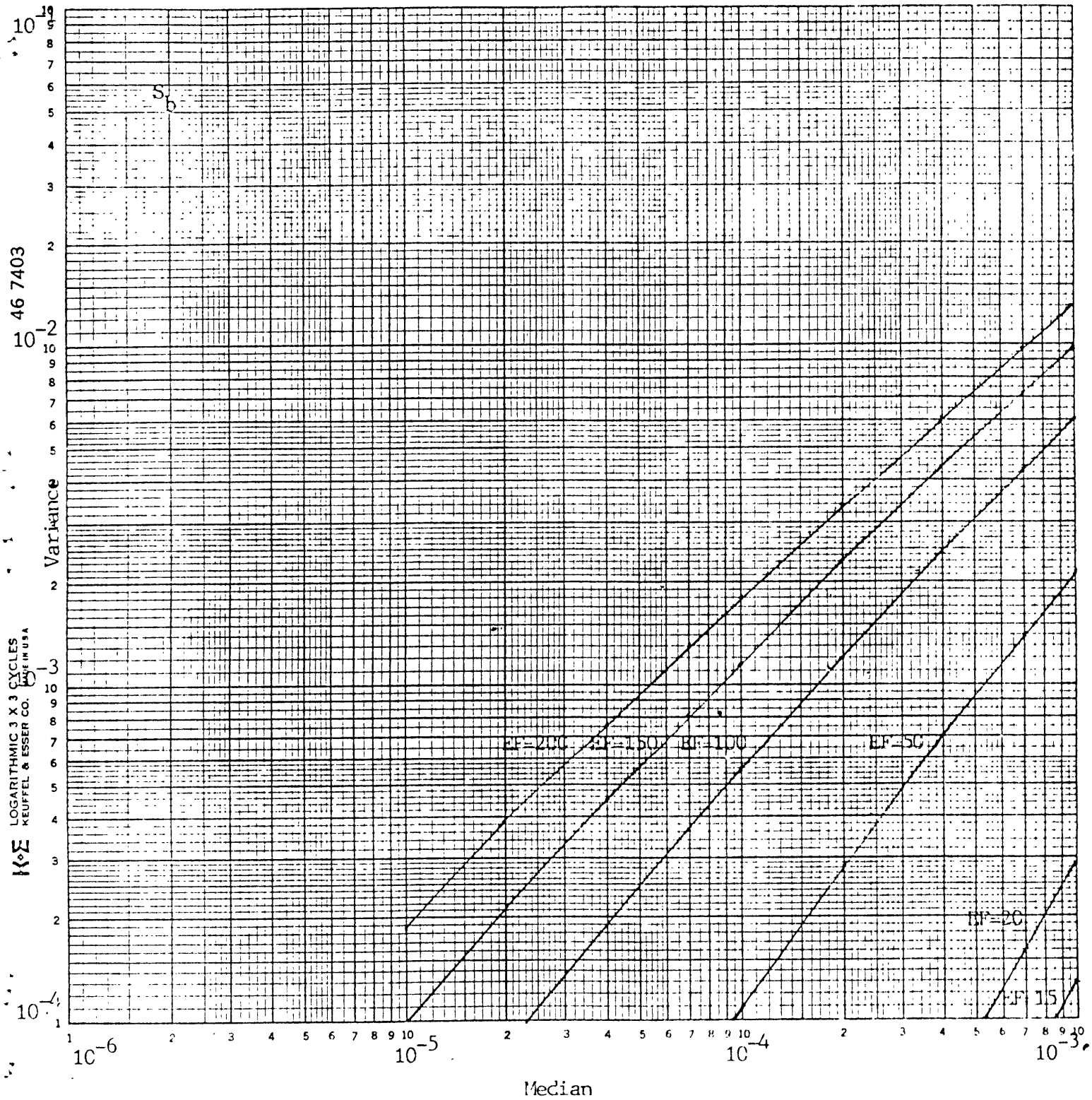
K+E LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO.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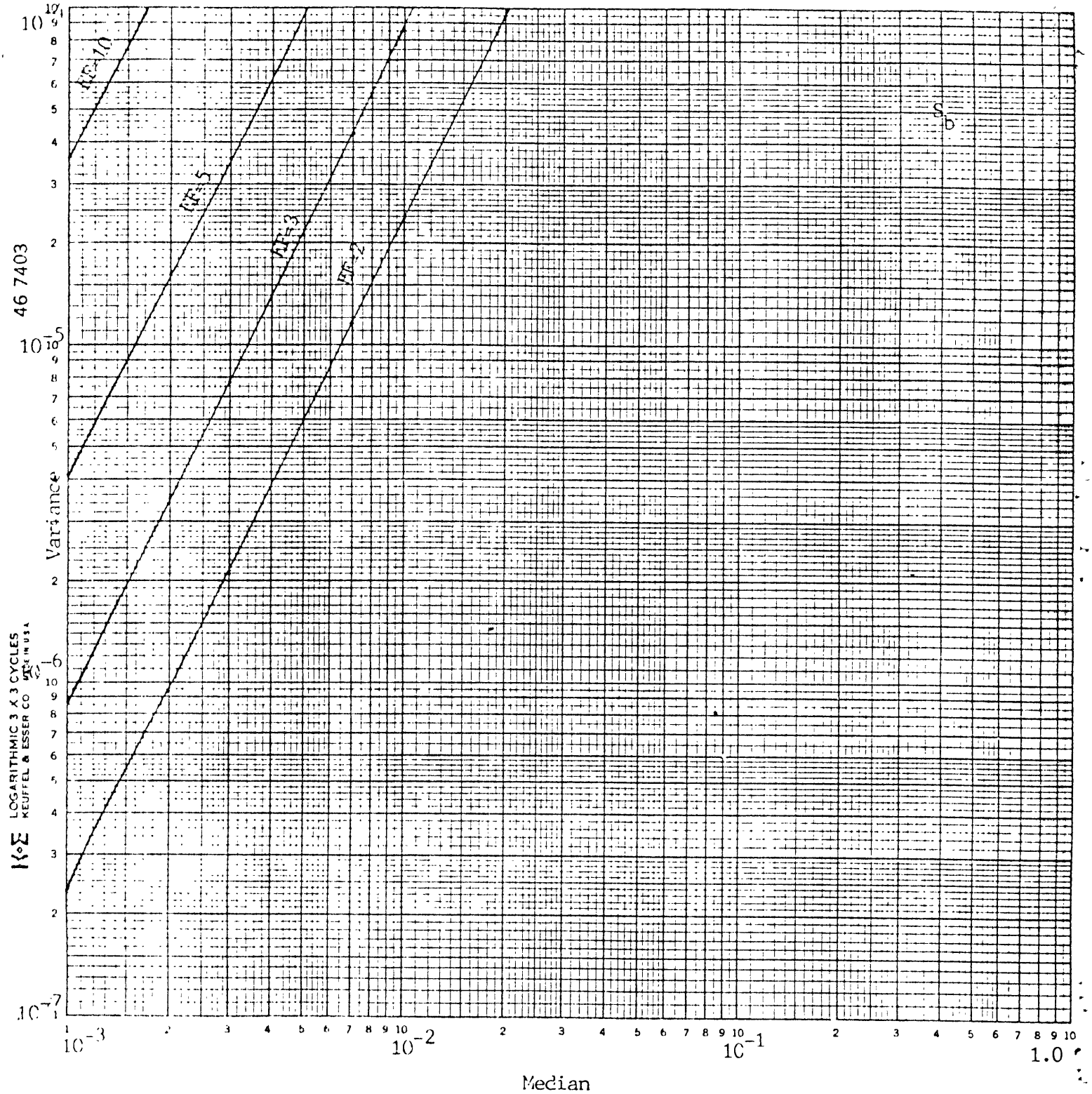
KEUFFEL & ESSER CO. MADE IN U.S.A.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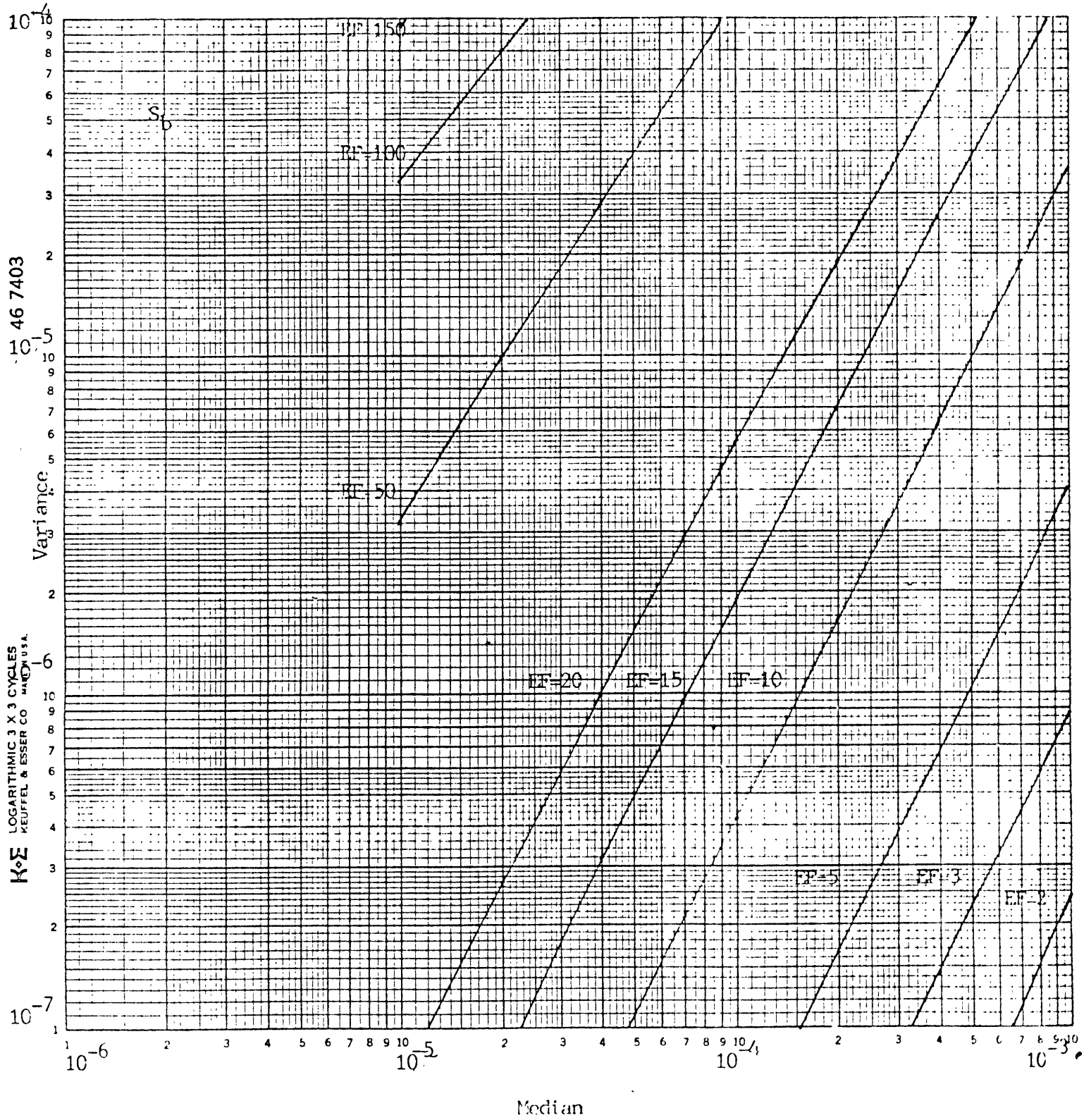
KEUFFEL & ESSER CO. MADE IN U.S.A.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Variance
Median
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10^{-6}
10^{-7}
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KEUFFEL & ESSER CO. MADE IN U.S.A.
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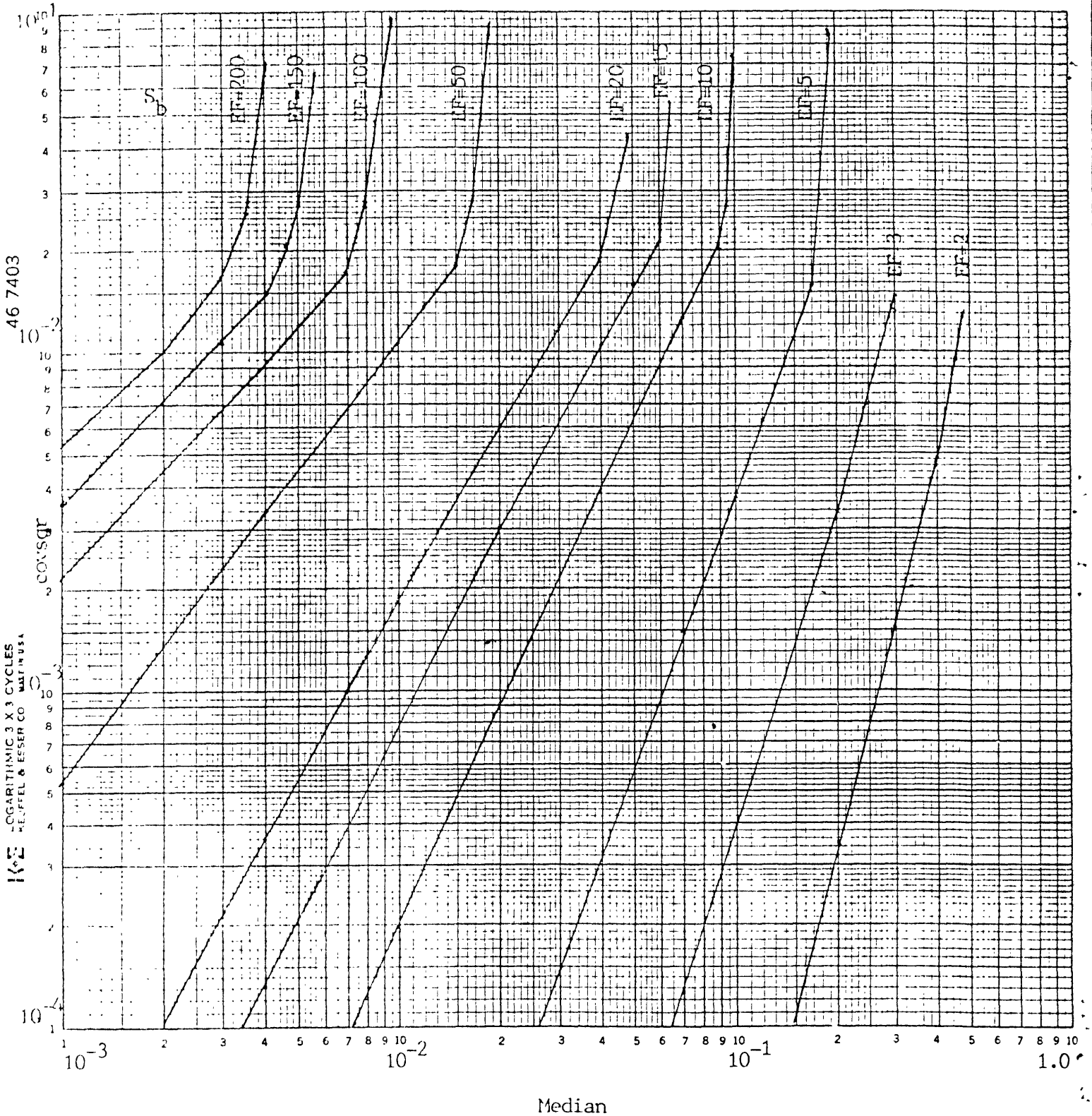
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COVSQR
Median
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46 7403
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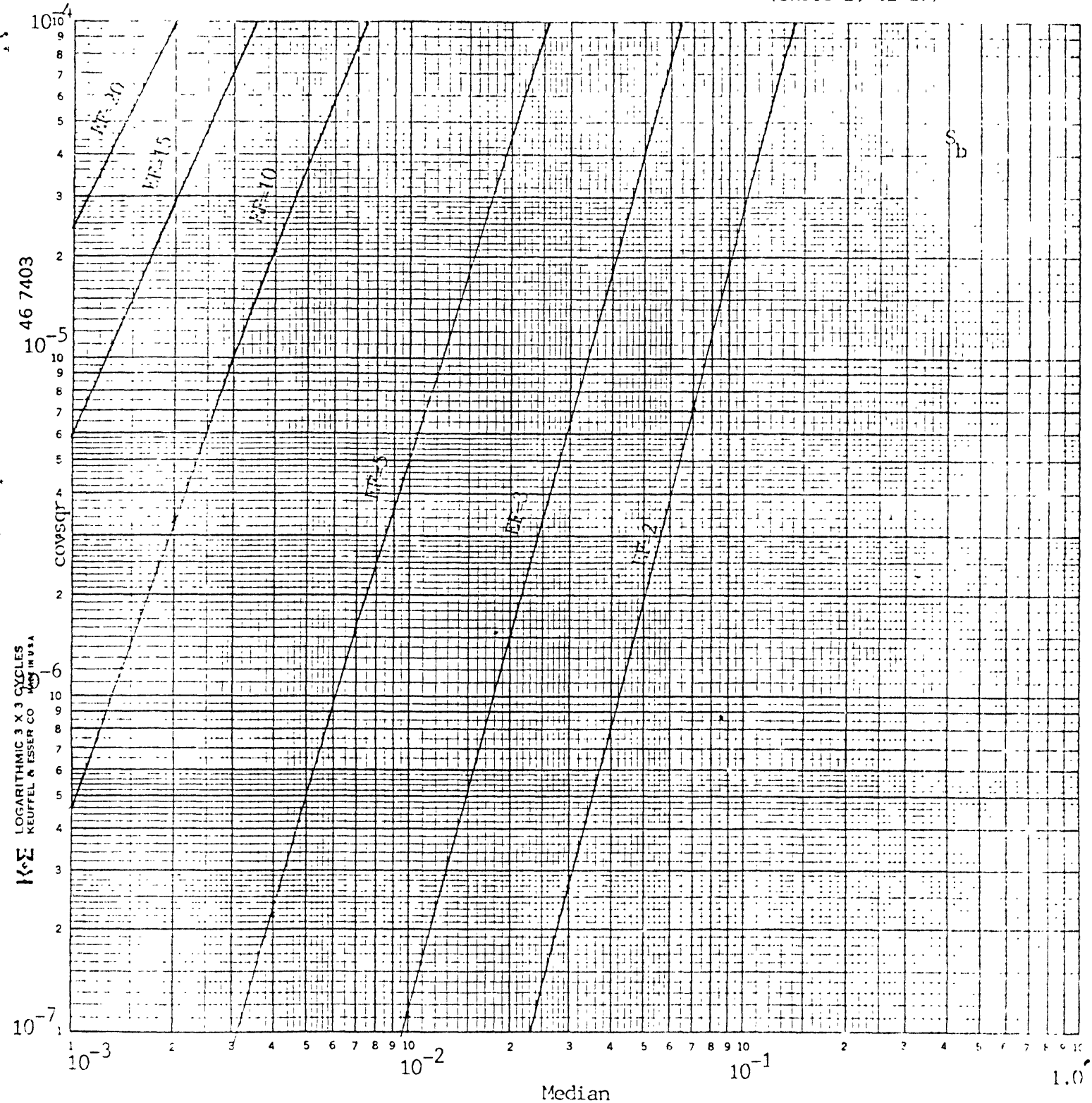
KEUFFEL & ESSER CO. MADE IN U.S.A.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S_b
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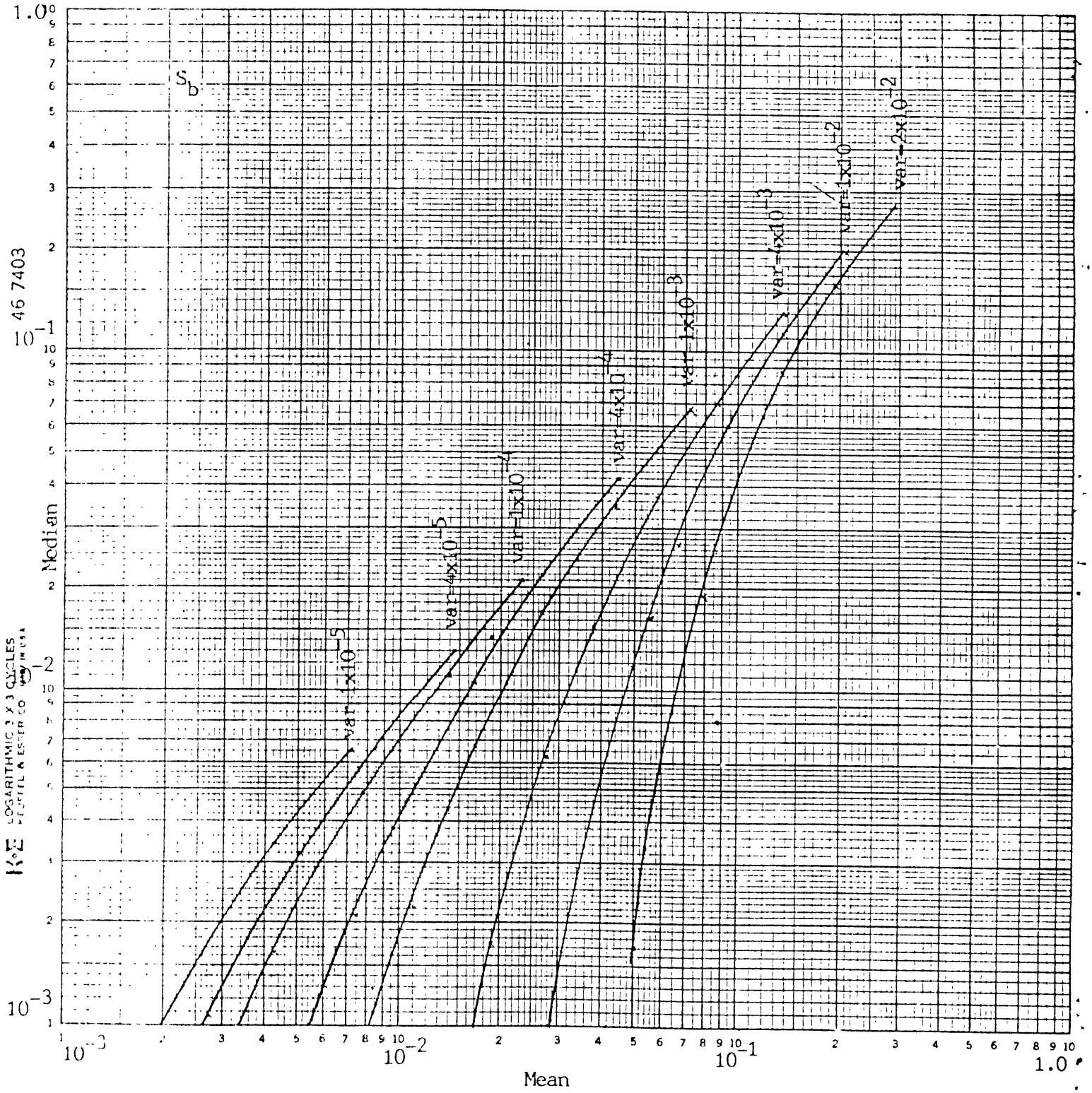
$E_r=3$
$E_r=2$
10^{-3}
10^{-2}
10^{-1}
1.0
Median
46 7403
K+E LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.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var=4x10^-3
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Median
Mean
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10^-1
10^-2
10^-3
46 7403
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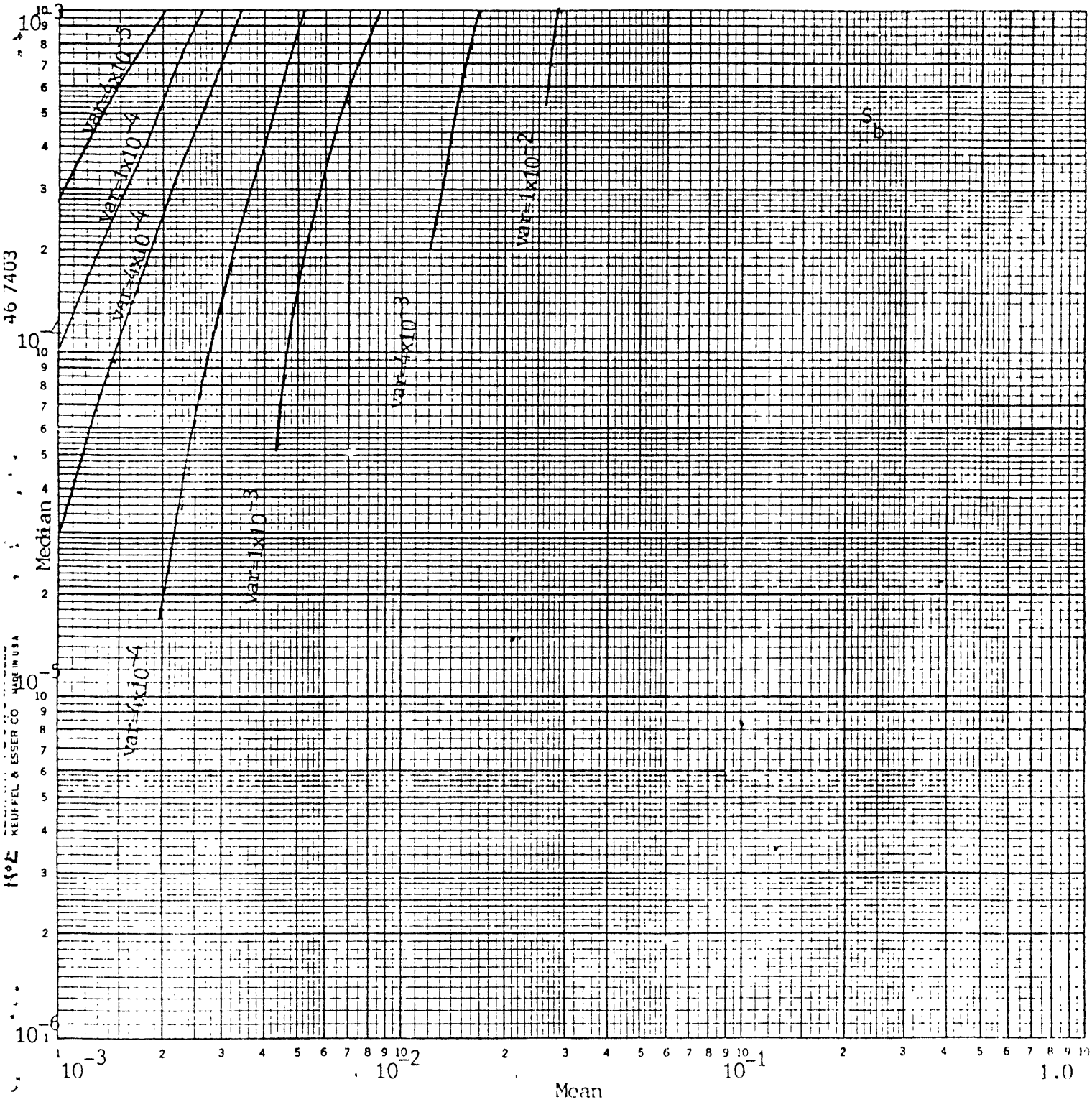
KEUFFEL & ESSER CO. MADE IN U.S.A.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Median
Mean
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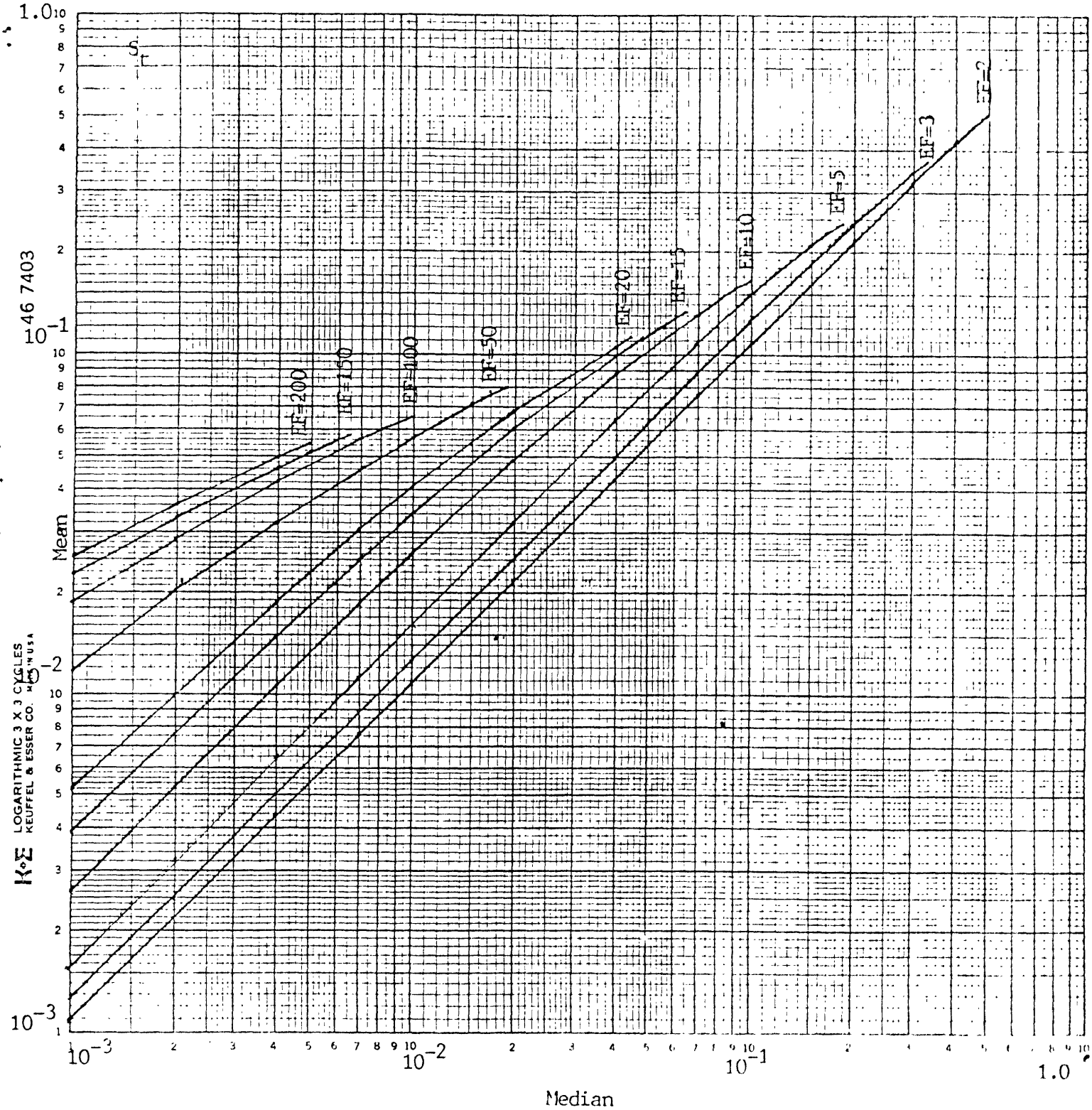
10^-2
10^-1
1.0
10^-4
10^-5
10^-6
46 7403
KEUFFEL & ESSER CO. MADE IN U.S.A.

Figure B2: The first four moments, variances and $E[(X_i-\bar{X}_i)^4]$ of the truncated log-normal distribution S_t. (12 Sheets)

(Sheet 1 of 12)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EF=2
Mean
Median
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10^{-2}
10^{-1}
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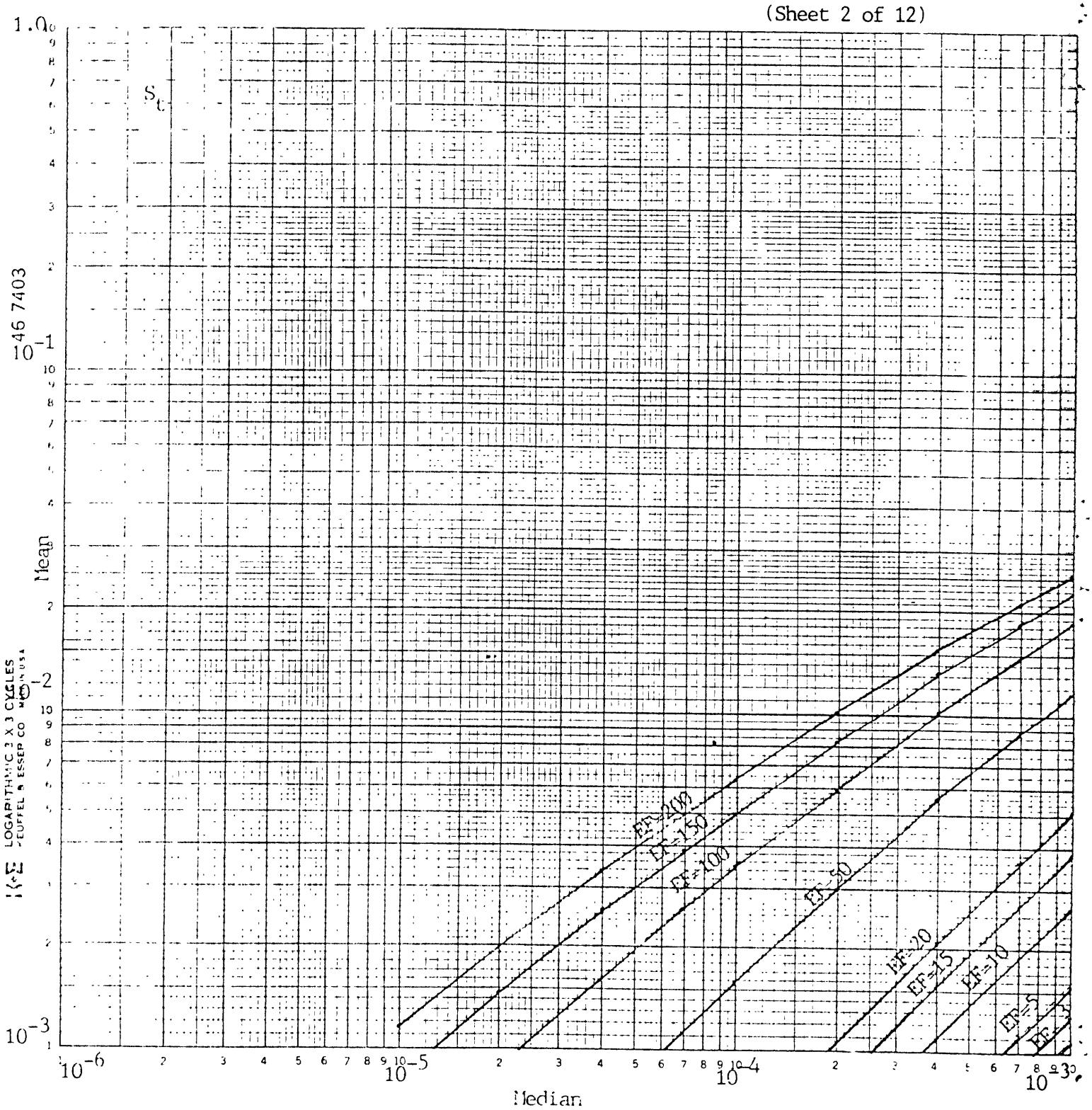
46 7403
K+E LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.

(Sheet 2 of 12)


S_t
Mean
Median
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10^{-4}
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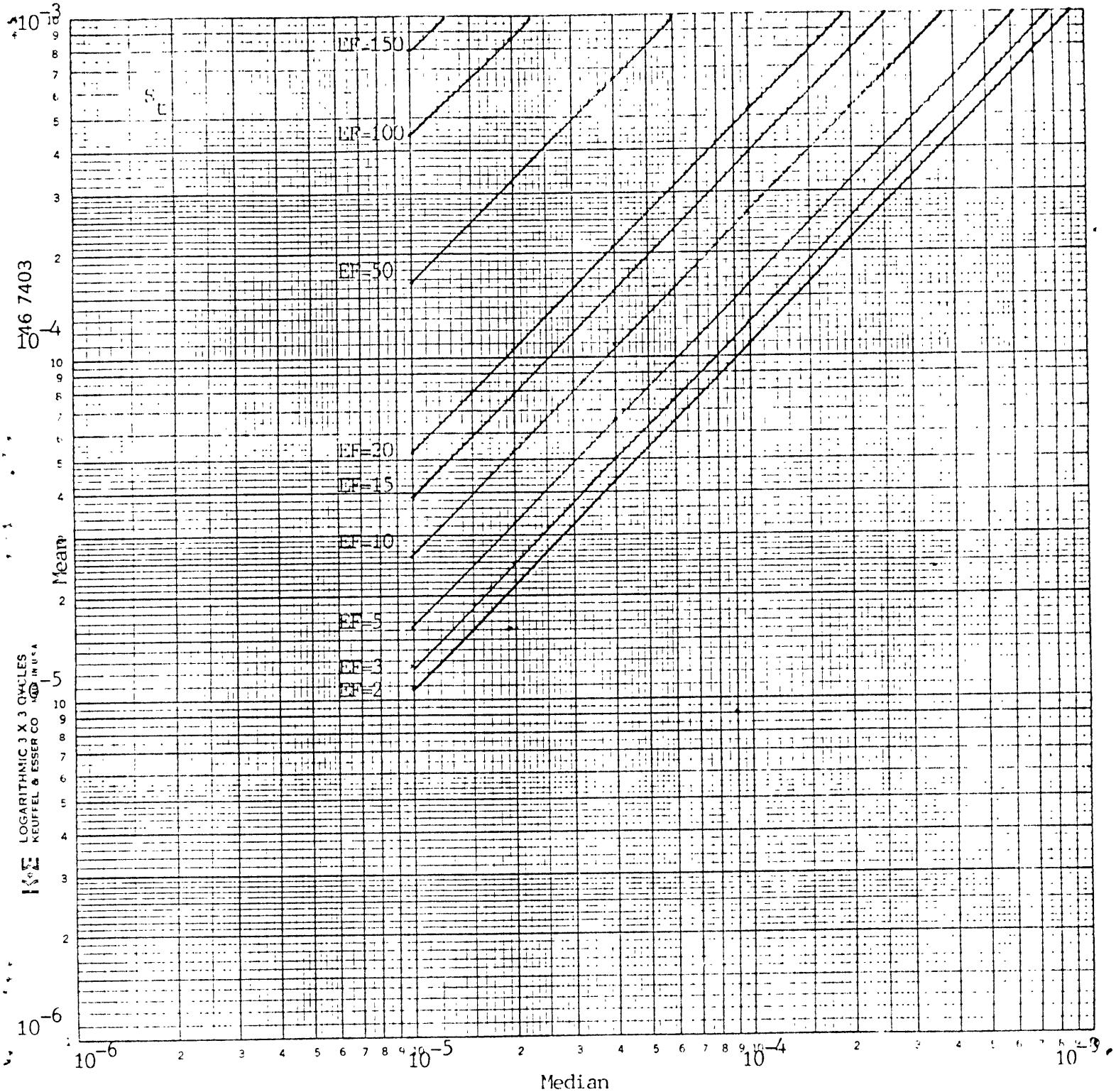
LOGARITHMIC 2 X 3 CYCLES
KEUFFEL & ESSER CO.
146 7403

(Sheet 3 of 12)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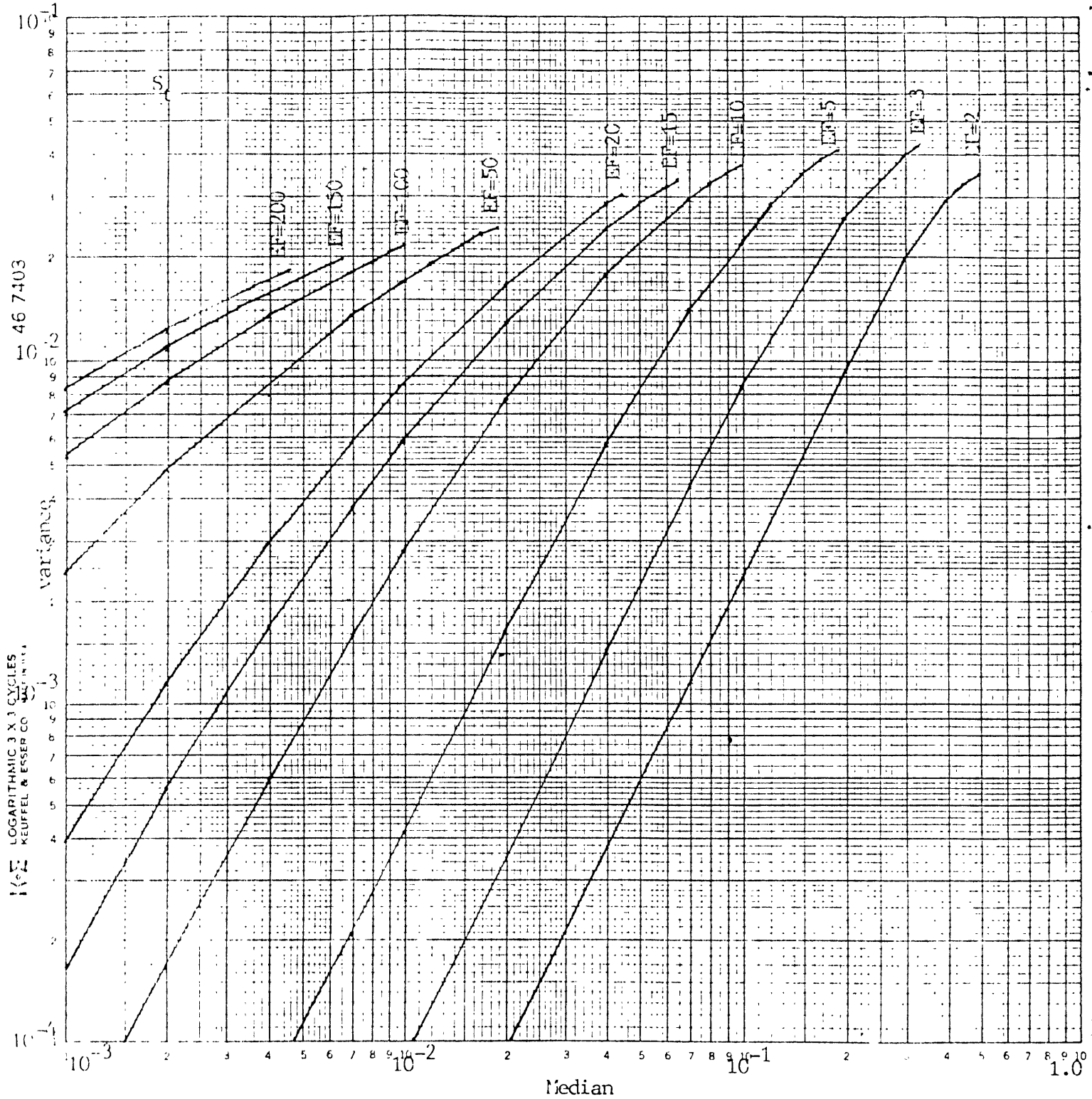
EF=3
EF=2
Mean
Median
10^{-3}
10^{-4}
10^{-5}
10^{-6}
46 7403
LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO.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Variance
Median
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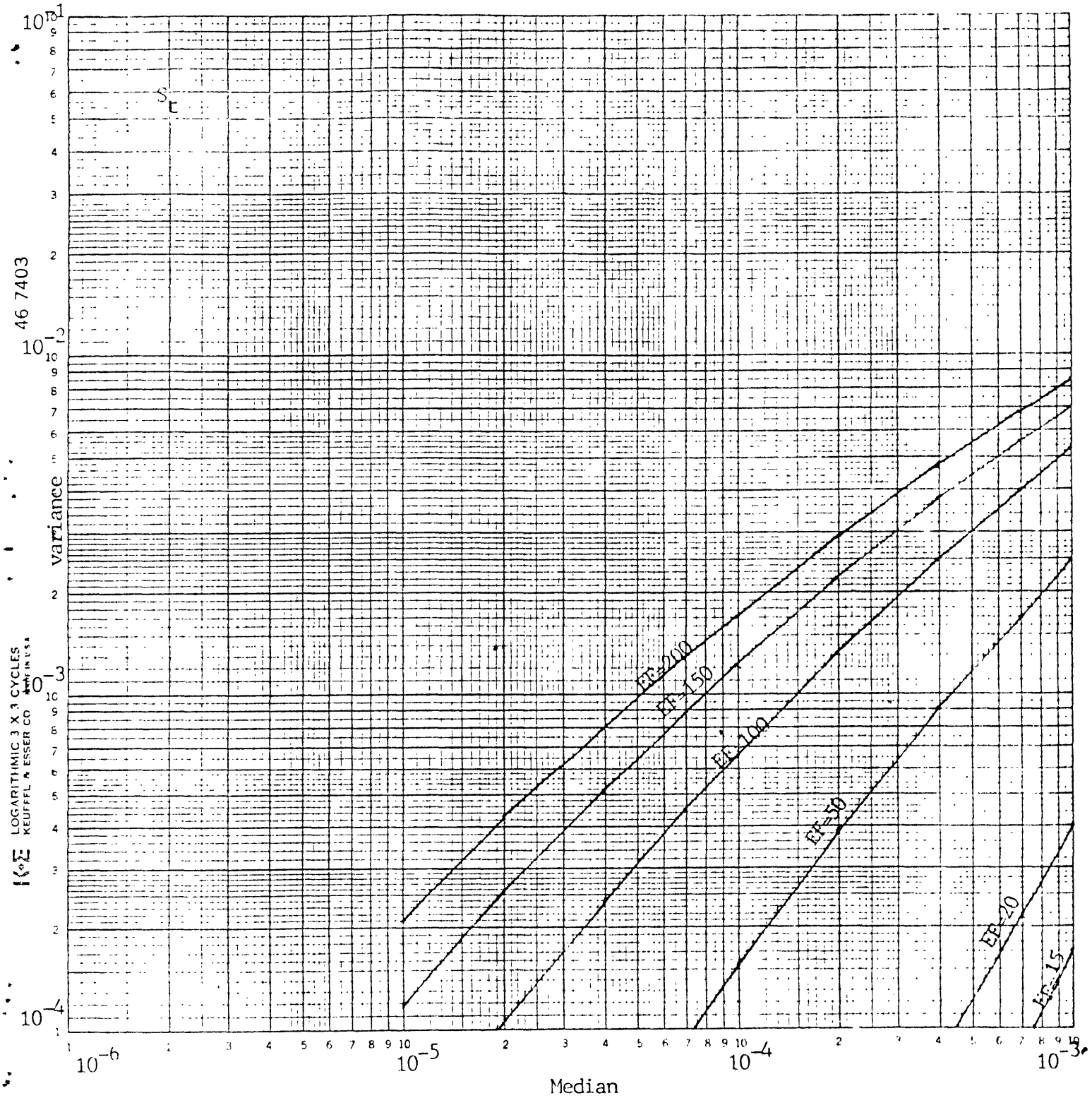
LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO.


S_t
variance
Median
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10^{-2}
10^{-3}
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10^{-6}
10^{-5}
10^{-4}
10^{-3}
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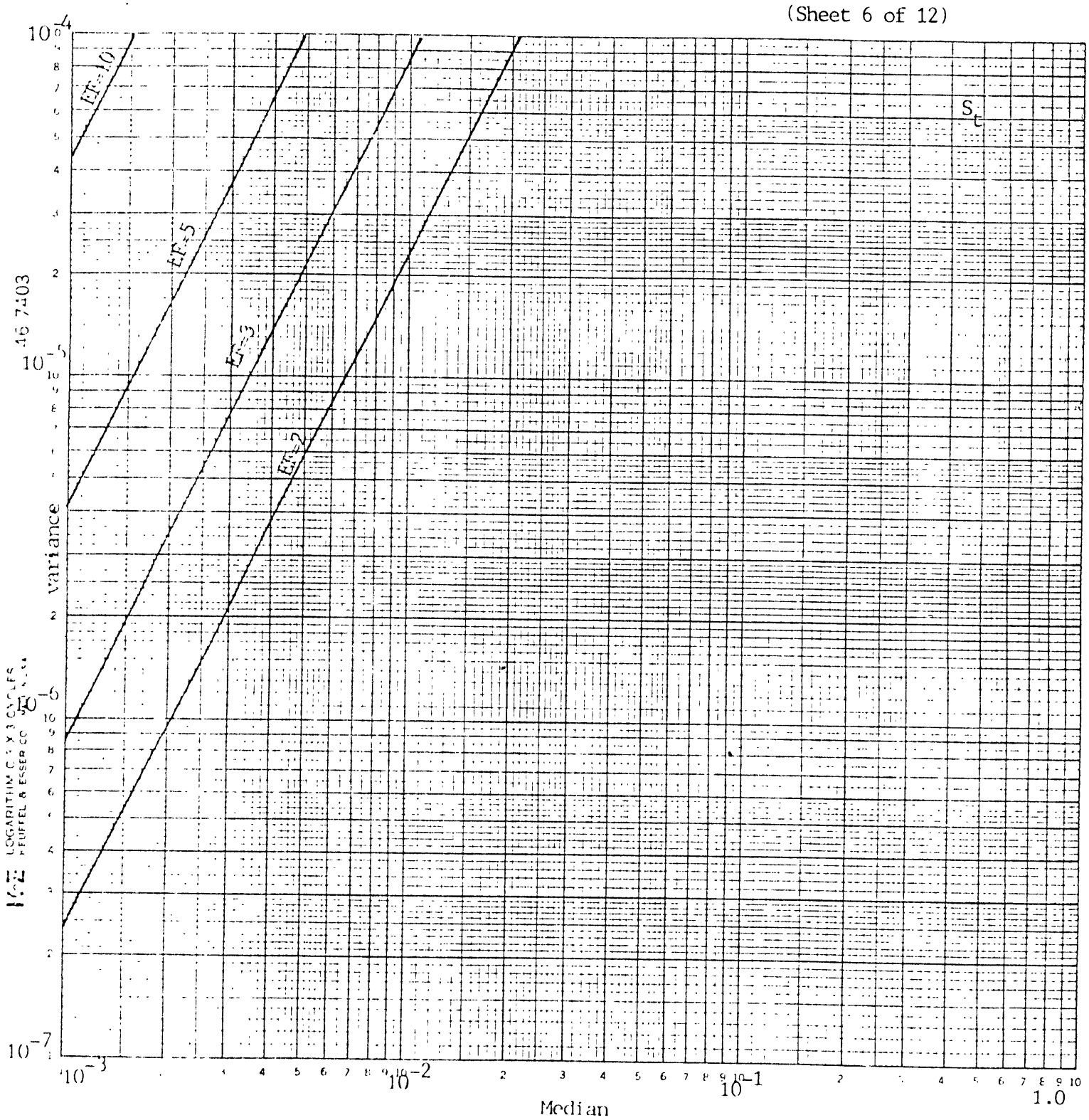
46 7403
LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.

(Sheet 6 of 12)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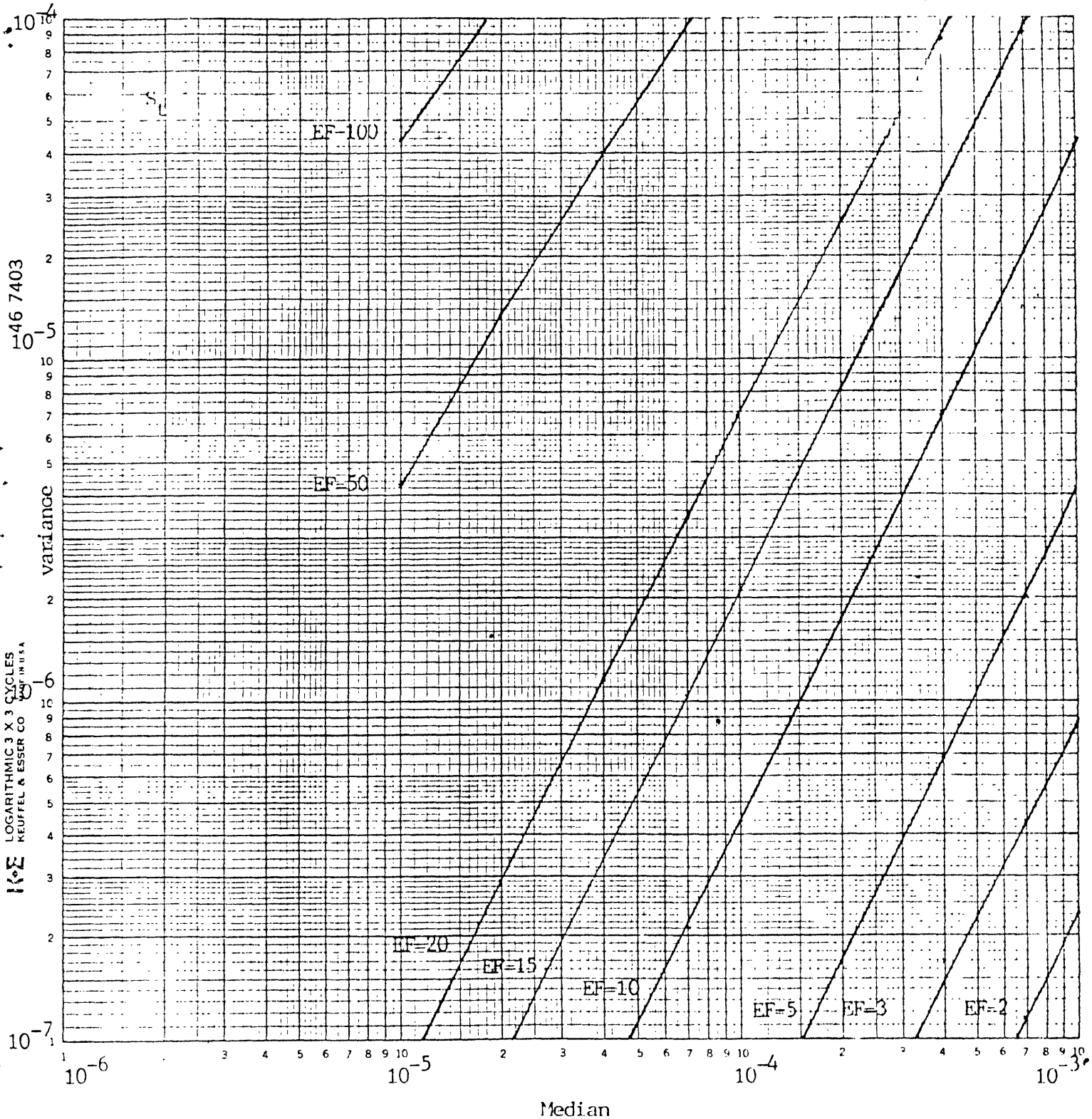
46 7403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EF=2
variance
Median
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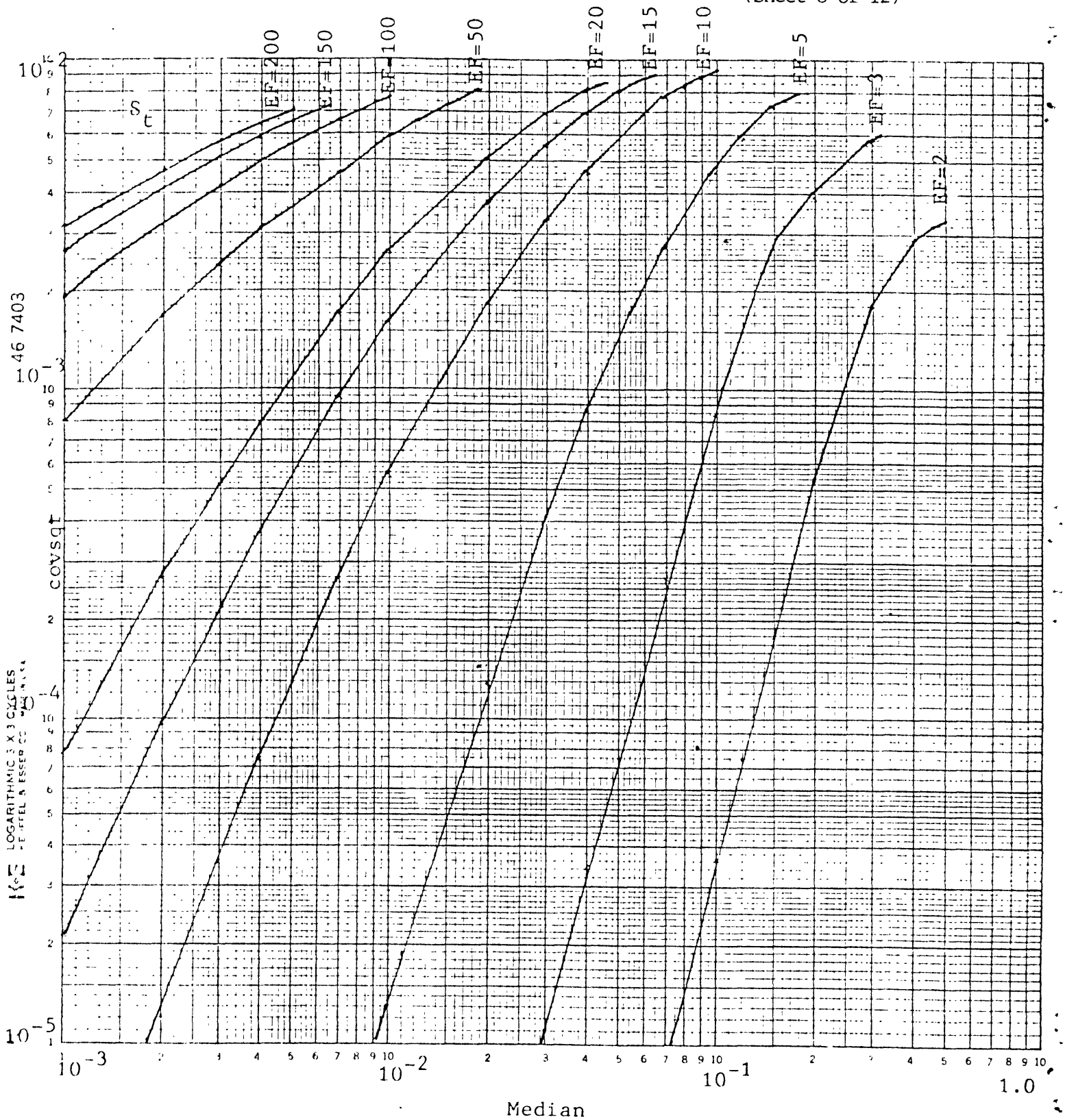
10^{-5}
10^{-6}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
46 7403
K+E LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.

(Sheet 8 of 12)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S_t
covsqt
Median
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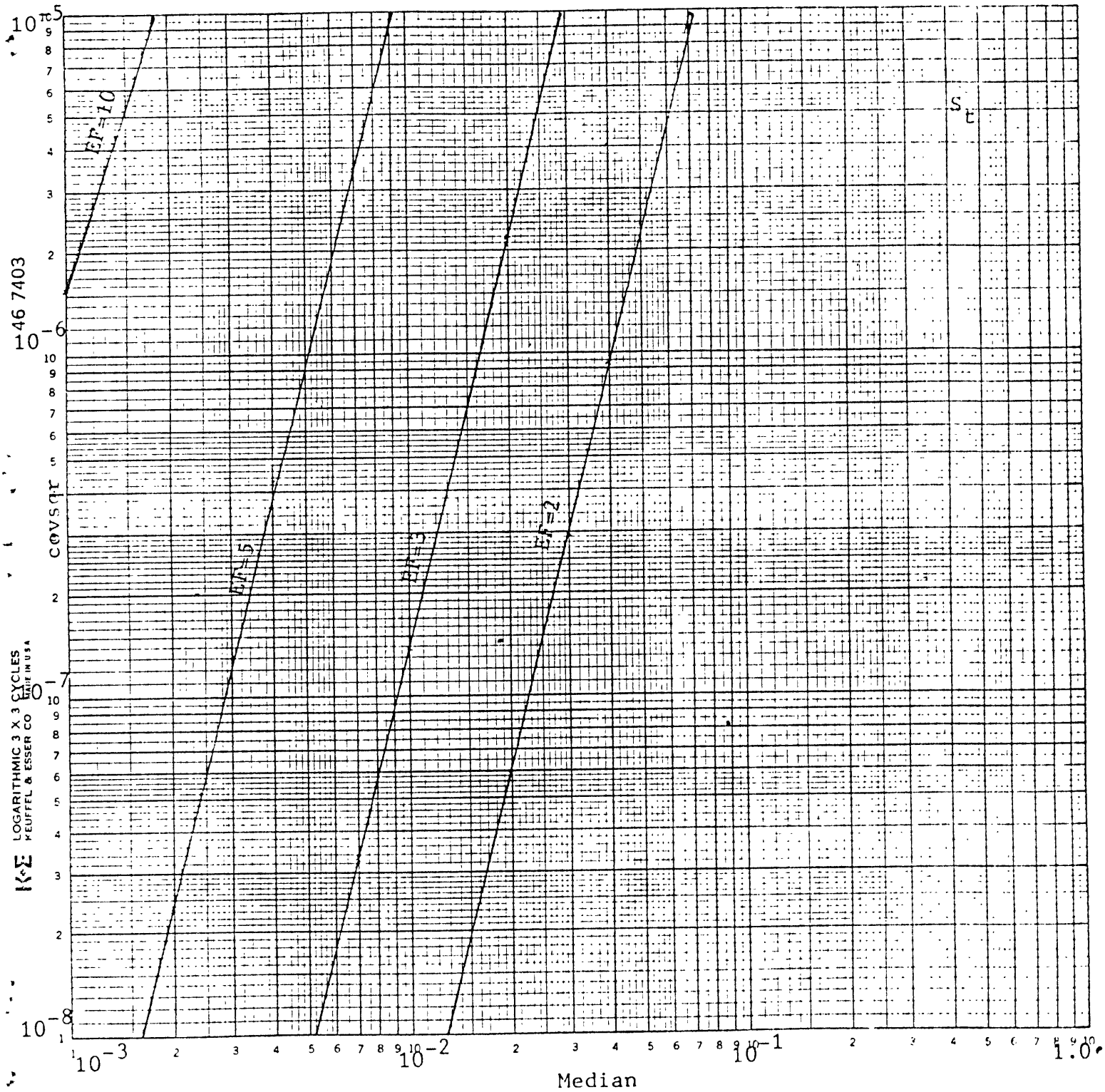
10^{-3}
10^{-4}
10^{-5}
46 7403

(Sheet 9 of 12)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Median
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10^{-1}
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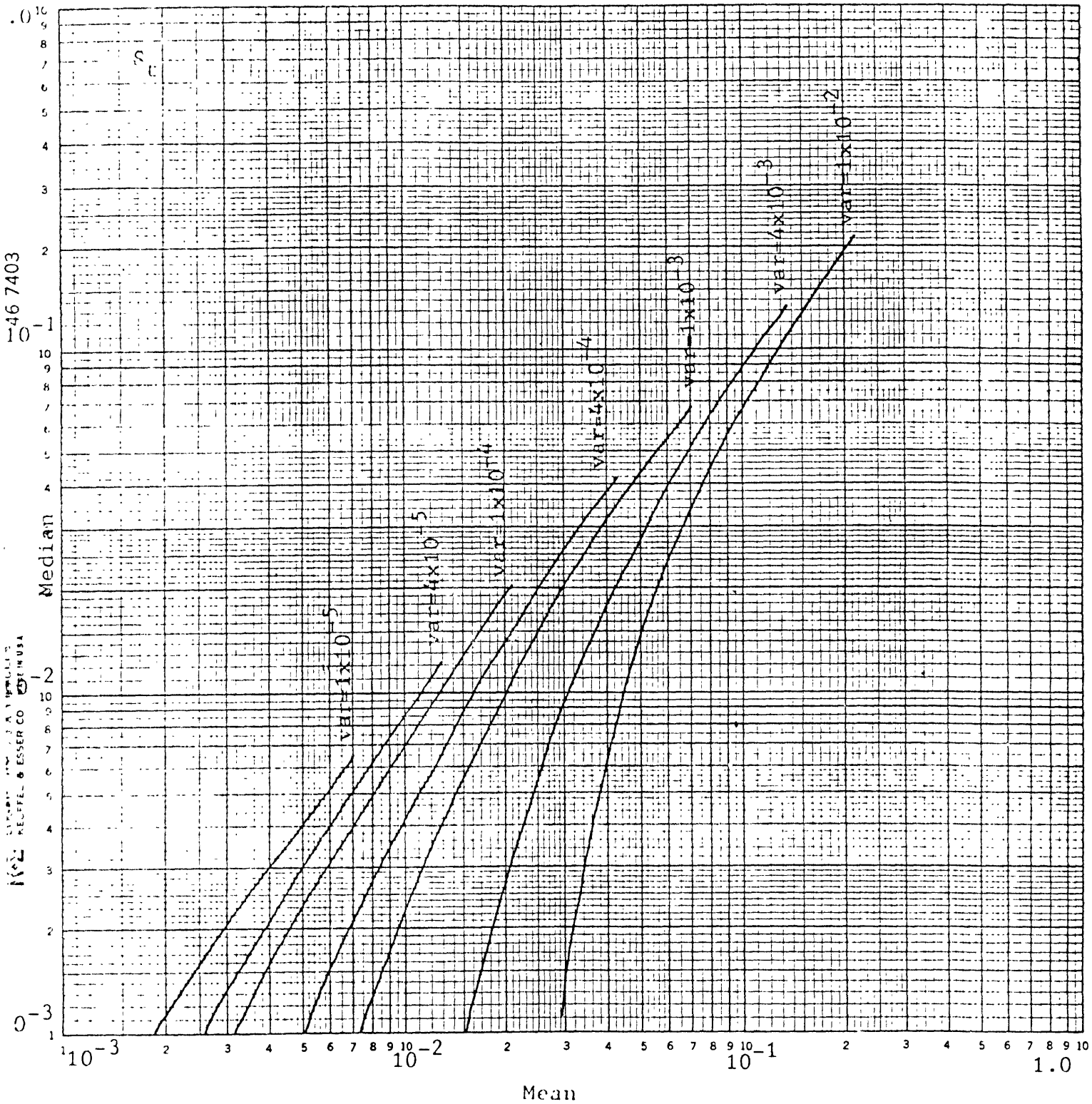
LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 7403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Median
Mean
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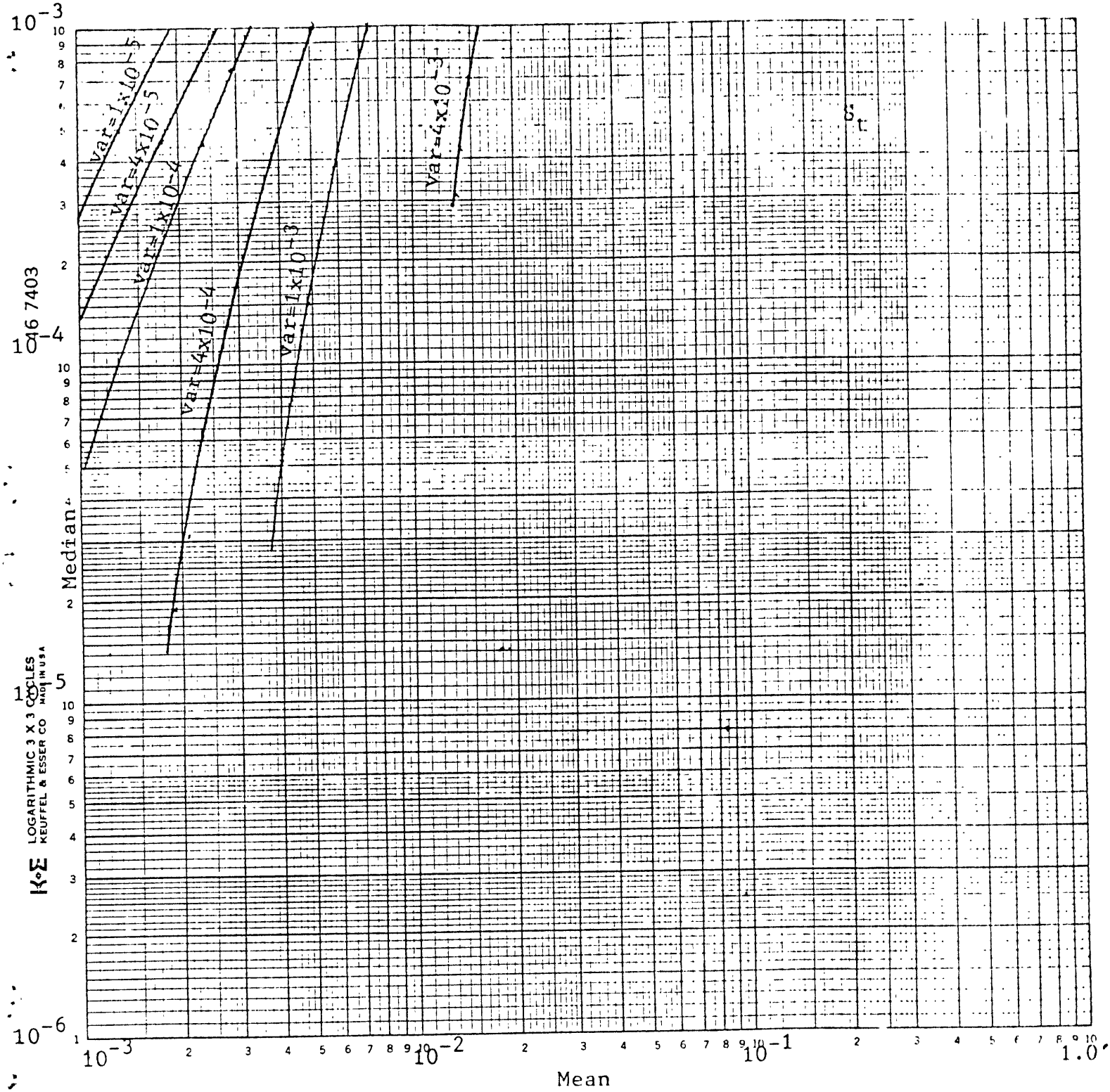
10^-2
10^-1
1.0

(Sheet 11 of 12)



46 7403

(Sheet 12 of 12)

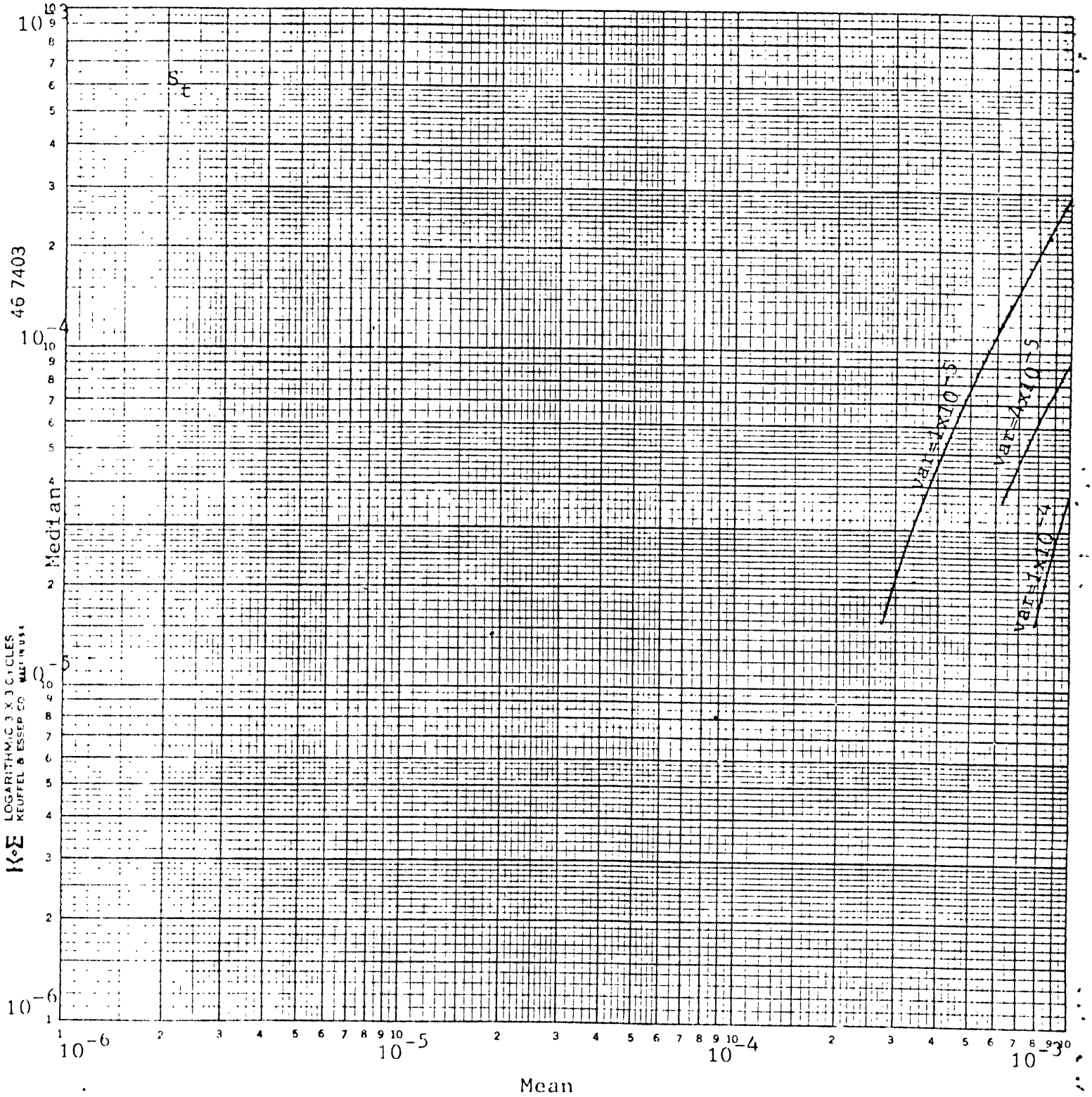


Table B1: The First Four Moments, Variances and $E[(X_i-\bar{X}_i)^4]$ of the bounded log-normal distribution S_b. (4 Sheets)

S_b

median	ef	m1	m2	m3	m4	variance	covsq
1.0E-01	2.0	1.09E-01	1.41E-02	2.17E-03	3.86E-04	2.35E-03	2.75E-05
1.0E-01	3.0	1.23E-01	2.30E-02	5.88E-03	1.89E-03	7.82E-03	3.98E-04
1.0E-01	5.0	1.56E-01	4.95E-02	2.23E-02	1.22E-02	2.50E-02	3.72E-03
2.0E-01	2.0	2.16E-01	5.60E-02	1.70E-02	5.85E-03	9.58E-03	3.49E-04
2.0E-01	3.0	2.44E-01	9.05E-02	4.27E-02	2.34E-02	3.08E-02	3.39E-03
3.0E-01	2.0	3.20E-01	1.25E-01	5.66E-02	2.85E-02	2.28E-02	1.52E-03
3.0E-01	3.0	3.67E-01	2.18E-01	1.54E-01	1.18E-01	8.33E-02	1.41E-02
4.0E-01	2.0	4.19E-01	2.23E-01	1.36E-01	9.02E-02	4.71E-02	4.87E-03
1.0E-02	2.0	1.09E-02	1.42E-04	2.22E-06	4.11E-08	2.35E-05	3.56E-09
1.0E-02	3.0	1.25E-02	2.42E-04	7.17E-06	3.17E-07	8.64E-05	1.13E-07
1.0E-02	5.0	1.60E-02	6.27E-04	5.18E-05	7.55E-06	3.70E-04	4.99E-06
1.0E-02	10.0	2.52E-02	2.75E-03	6.79E-04	2.55E-04	2.12E-03	1.96E-04
1.0E-02	15.0	3.39E-02	6.04E-03	2.19E-03	1.08E-03	4.89E-03	8.25E-04
1.0E-02	20.0	4.19E-02	9.92E-03	4.36E-03	2.47E-03	8.16E-03	1.84E-03
1.0E-02	50.0	8.16E-02	3.60E-02	2.29E-02	1.68E-02	2.93E-02	1.06E-02
2.0E-02	2.0	2.18E-02	5.69E-04	1.77E-05	6.52E-07	9.38E-05	5.52E-08
2.0E-02	3.0	2.49E-02	9.61E-04	5.56E-05	4.64E-06	3.40E-04	1.52E-06
2.0E-02	5.0	3.19E-02	2.38E-03	3.39E-04	7.60E-05	1.36E-03	4.41E-05
2.0E-02	10.0	4.91E-02	8.87E-03	3.02E-03	1.40E-03	6.46E-03	9.22E-04
2.0E-02	15.0	6.49E-02	1.76E-02	8.13E-03	4.73E-03	1.34E-02	3.01E-03
2.0E-02	20.0	7.96E-02	2.75E-02	1.49E-02	9.68E-03	2.11E-02	5.87E-03
3.0E-02	2.0	3.27E-02	1.28E-03	5.95E-05	3.28E-06	2.11E-04	2.71E-07
3.0E-02	3.0	3.73E-02	2.15E-03	1.82E-04	2.18E-05	7.55E-04	6.66E-06
3.0E-02	5.0	4.76E-02	5.13E-03	9.90E-04	2.80E-04	2.87E-03	1.46E-04
3.0E-02	10.0	7.25E-02	1.75E-02	7.17E-03	3.79E-03	1.22E-02	2.18E-03
3.0E-02	15.0	9.57E-02	3.35E-02	1.80E-02	1.16E-02	2.43E-02	6.29E-03
3.0E-02	20.0	1.19E-01	5.18E-02	3.22E-02	2.30E-02	3.78E-02	1.15E-02
4.0E-02	2.0	4.36E-02	2.27E-03	1.41E-04	1.03E-05	3.75E-04	8.31E-07
4.0E-02	3.0	4.97E-02	3.79E-03	4.22E-04	6.44E-05	1.32E-03	1.85E-05
4.0E-02	5.0	6.32E-02	8.82E-03	2.09E-03	6.96E-04	4.83E-03	3.31E-04
4.0E-02	10.0	9.59E-02	2.85E-02	1.33E-02	7.75E-03	1.93E-02	3.95E-03
4.0E-02	15.0	1.28E-01	5.42E-02	3.27E-02	2.28E-02	3.78E-02	1.06E-02
4.0E-02	20.0	1.63E-01	8.53E-02	5.92E-02	4.55E-02	5.86E-02	1.84E-02
7.0E-02	2.0	7.61E-02	6.94E-03	7.49E-04	9.45E-05	1.15E-03	7.15E-06
7.0E-02	3.0	8.67E-02	1.14E-02	2.12E-03	5.14E-04	3.92E-03	1.25E-04
7.0E-02	5.0	1.10E-01	2.52E-02	8.86E-03	3.99E-03	1.32E-02	1.49E-03
7.0E-02	10.0	1.71E-01	7.82E-02	4.87E-02	3.47E-02	4.91E-02	1.25E-02
1.0E-03	2.0	1.09E-03	1.43E-06	2.22E-09	4.14E-12	2.35E-07	3.67E-13
1.0E-03	3.0	1.25E-03	2.44E-06	7.41E-09	3.50E-11	8.78E-07	1.35E-11
1.0E-03	5.0	1.61E-03	6.72E-06	7.03E-08	1.73E-09	4.12E-06	1.36E-09
1.0E-03	10.0	2.64E-03	4.34E-05	2.97E-06	4.91E-07	3.65E-05	4.62E-07
1.0E-03	15.0	3.76E-03	1.41E-04	2.11E-05	6.16E-06	1.27E-04	5.86E-06
1.0E-03	20.0	4.93E-03	3.08E-04	6.79E-05	2.56E-05	2.83E-04	2.43E-05
1.0E-03	50.0	1.17E-02	2.28E-03	9.92E-04	5.75E-04	2.14E-03	5.30E-04
1.0E-03	100.0	2.10E-02	6.54E-03	3.61E-03	2.42E-03	6.10E-03	2.14E-03
1.0E-03	150.0	2.82E-02	1.05E-02	6.34E-03	4.49E-03	9.74E-03	3.82E-03
1.0E-03	200.0	3.41E-02	1.41E-02	8.89E-03	6.48E-03	1.29E-02	5.36E-03
2.0E-03	2.0	2.18E-03	5.70E-06	1.78E-08	6.61E-11	9.39E-07	5.85E-12
2.0E-03	3.0	2.50E-03	9.74E-06	5.91E-08	5.53E-10	3.51E-06	2.11E-10
2.0E-03	5.0	3.22E-03	2.66E-05	5.36E-07	2.38E-08	1.62E-05	1.83E-08
2.0E-03	10.0	5.24E-03	1.58E-04	1.67E-05	3.65E-06	1.31E-04	3.32E-06
2.0E-03	15.0	7.37E-03	4.59E-04	9.22E-05	3.19E-05	4.05E-04	2.93E-05
2.0E-03	20.0	9.51E-03	9.16E-04	2.52E-04	1.08E-04	8.26E-04	9.86E-05
2.0E-03	50.0	2.10E-02	5.23E-03	2.53E-03	1.56E-03	4.79E-03	1.36E-03
2.0E-03	100.0	3.55E-02	1.31E-02	7.78E-03	5.45E-03	1.18E-02	4.44E-03

S_b

median	ef	m1	m2	m3	m4	variance	covsq
2.0E-03	150.0	4.64E-02	2.00E-02	1.28E-02	9.43E-03	1.79E-02	7.29E-03
2.0E-03	200.0	5.54E-02	2.64E-02	1.77E-02	1.34E-02	2.33E-02	9.96E-03
3.0E-03	2.0	3.27E-03	1.28E-05	6.00E-08	3.34E-10	2.11E-06	2.95E-11
3.0E-03	3.0	3.75E-03	2.19E-05	1.99E-07	2.77E-09	7.87E-06	1.05E-09
3.0E-03	5.0	4.83E-03	5.94E-05	1.74E-06	1.07E-07	3.60E-05	7.99E-08
3.0E-03	10.0	7.81E-03	3.32E-04	4.43E-05	1.12E-05	2.71E-04	9.91E-06
3.0E-03	15.0	1.09E-02	8.97E-04	2.11E-04	8.01E-05	7.79E-04	7.15E-05
3.0E-03	20.0	1.39E-02	1.70E-03	5.27E-04	2.42E-04	1.50E-03	2.14E-04
3.0E-03	50.0	2.94E-02	8.41E-03	4.34E-03	2.78E-03	7.55E-03	2.31E-03
3.0E-03	100.0	4.83E-02	1.98E-02	1.23E-02	8.87E-03	1.74E-02	6.75E-03
3.0E-03	150.0	6.29E-02	2.98E-02	2.00E-02	1.51E-02	2.59E-02	1.07E-02
3.0E-03	200.0	7.61E-02	4.30E-02	3.11E-02	2.48E-02	3.73E-02	1.68E-02
4.0E-03	2.0	4.36E-03	2.28E-05	1.42E-07	1.06E-09	3.76E-06	9.29E-11
4.0E-03	3.0	4.99E-03	3.89E-05	4.69E-07	8.65E-09	1.40E-05	3.24E-09
4.0E-03	5.0	6.43E-03	1.05E-04	3.96E-06	3.04E-07	6.33E-05	2.22E-07
4.0E-03	10.0	1.04E-02	5.56E-04	8.68E-05	2.42E-05	4.49E-04	2.10E-05
4.0E-03	15.0	1.43E-02	1.43E-03	3.74E-04	1.52E-04	1.23E-03	1.32E-04
4.0E-03	20.0	1.81E-02	2.61E-03	8.81E-04	4.25E-04	2.28E-03	3.66E-04
4.0E-03	50.0	3.73E-02	1.18E-02	6.38E-03	4.20E-03	1.04E-02	3.34E-03
4.0E-03	100.0	6.05E-02	2.67E-02	1.72E-02	1.27E-02	2.31E-02	9.09E-03
4.0E-03	150.0	7.93E-02	4.17E-02	2.93E-02	2.29E-02	3.55E-02	1.51E-02
4.0E-03	200.0	9.74E-02	1.29E-01	1.10E-01	9.93E-02	1.20E-01	6.34E-02
7.0E-03	2.0	7.64E-03	6.98E-05	7.61E-07	9.88E-09	1.15E-05	8.63E-10
7.0E-03	3.0	8.74E-03	1.19E-04	2.49E-06	7.85E-08	4.26E-05	2.86E-08
7.0E-03	5.0	1.12E-02	3.13E-04	1.93E-05	2.21E-06	1.87E-04	1.53E-06
7.0E-03	10.0	1.79E-02	1.49E-03	3.09E-04	1.04E-04	1.17E-03	8.42E-05
7.0E-03	15.0	2.43E-02	3.47E-03	1.11E-03	5.08E-04	2.88E-03	4.12E-04
7.0E-03	20.0	3.03E-02	5.92E-03	2.35E-03	1.25E-03	5.00E-03	9.94E-04
7.0E-03	50.0	5.97E-02	2.30E-02	1.37E-02	9.59E-03	1.94E-02	6.77E-03
7.0E-03	100.0	9.78E-02	5.29E-02	3.76E-02	2.96E-02	4.34E-02	1.76E-02
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1.0E-04	3.0	1.25E-04	2.44E-08	7.44E-12	3.54E-15	8.80E-09	1.38E-15
1.0E-04	5.0	1.61E-04	6.78E-08	7.38E-11	2.07E-13	4.17E-08	1.68E-13
1.0E-04	10.0	2.66E-04	4.93E-07	5.62E-09	2.73E-10	4.22E-07	2.67E-10
1.0E-04	15.0	3.86E-04	2.03E-06	8.66E-08	1.24E-08	1.88E-06	1.23E-08
1.0E-04	20.0	5.20E-04	5.78E-06	5.03E-07	1.15E-07	5.51E-06	1.14E-07
1.0E-04	50.0	1.51E-03	1.11E-04	3.27E-05	1.53E-05	1.08E-04	1.51E-05
1.0E-04	100.0	3.36E-03	5.68E-04	2.47E-04	1.45E-04	5.57E-04	1.42E-04
1.0E-04	150.0	5.15E-03	1.19E-03	5.95E-04	3.78E-04	1.16E-03	3.66E-04
1.0E-04	200.0	6.79E-03	1.86E-03	9.99E-04	6.62E-04	1.81E-03	6.36E-04
2.0E-04	2.0	2.18E-04	5.70E-08	1.78E-11	6.62E-15	9.39E-09	5.88E-16
2.0E-04	3.0	2.50E-04	9.76E-08	5.95E-11	5.66E-14	3.52E-08	2.20E-14
2.0E-04	5.0	3.23E-04	2.71E-07	5.87E-10	3.23E-12	1.67E-07	2.61E-12
2.0E-04	10.0	5.32E-04	1.93E-06	3.99E-08	2.96E-09	1.65E-06	2.88E-09
2.0E-04	15.0	7.70E-04	7.59E-06	4.98E-07	9.13E-08	6.99E-06	8.98E-08
2.0E-04	20.0	1.03E-03	2.02E-05	2.42E-06	6.55E-07	1.91E-05	6.45E-07
2.0E-04	50.0	2.85E-03	2.90E-04	9.71E-05	4.86E-05	2.82E-04	4.75E-05
2.0E-04	100.0	5.96E-03	1.23E-03	5.76E-04	3.52E-04	1.20E-03	3.39E-04
2.0E-04	150.0	8.76E-03	2.36E-03	1.25E-03	8.17E-04	2.28E-03	7.75E-04
2.0E-04	200.0	1.12E-02	3.49E-03	1.96E-03	1.34E-03	3.36E-03	1.25E-03
3.0E-04	2.0	3.27E-04	1.28E-07	6.00E-11	3.35E-14	2.11E-08	2.98E-15
3.0E-04	3.0	3.75E-04	2.20E-07	2.01E-10	2.86E-13	7.91E-08	1.11E-13
3.0E-04	5.0	4.84E-04	6.09E-07	1.97E-09	1.60E-11	3.74E-07	1.29E-11
3.0E-04	10.0	7.97E-04	4.28E-06	1.22E-07	1.14E-08	3.65E-06	1.10E-08
3.0E-04	15.0	1.15E-03	1.62E-05	1.33E-06	2.79E-07	1.48E-05	2.73E-07

S_b

median	ef	m1	m2	m3	m4	variance	covsq
3.0E-04	20.0	1.54E-03	4.11E-05	5.83E-06	1.73E-06	3.87E-05	1.69E-06
3.0E-04	50.0	4.11E-03	4.98E-04	1.79E-04	9.30E-05	4.81E-04	9.01E-05
3.0E-04	100.0	8.26E-03	1.91E-03	9.28E-04	5.81E-04	1.84E-03	5.51E-04
3.0E-04	150.0	1.18E-02	3.47E-03	1.89E-03	1.27E-03	3.33E-03	1.18E-03
3.0E-04	200.0	1.49E-02	4.99E-03	2.89E-03	2.00E-03	4.76E-03	1.83E-03
4.0E-04	2.0	4.37E-04	2.28E-07	1.42E-10	1.06E-13	3.76E-08	9.40E-15
4.0E-04	3.0	5.00E-04	3.90E-07	4.76E-10	9.03E-13	1.41E-07	3.50E-13
4.0E-04	5.0	6.45E-04	1.08E-06	4.64E-09	4.95E-11	6.65E-07	3.97E-11
4.0E-04	10.0	1.06E-03	7.49E-06	2.67E-07	2.89E-08	6.37E-06	2.78E-08
4.0E-04	15.0	1.53E-03	2.74E-05	2.64E-06	6.01E-07	2.51E-05	5.85E-07
4.0E-04	20.0	2.03E-03	6.74E-05	1.07E-05	3.37E-06	6.32E-05	3.29E-06
4.0E-04	50.0	5.31E-03	7.24E-04	2.73E-04	1.46E-04	6.96E-04	1.40E-04
4.0E-04	100.0	1.04E-02	2.57E-03	1.29E-03	8.23E-04	2.46E-03	7.71E-04
4.0E-04	150.0	1.46E-02	4.54E-03	2.54E-03	1.72E-03	4.33E-03	1.58E-03
4.0E-04	200.0	1.82E-02	6.40E-03	3.78E-03	2.65E-03	6.07E-03	2.38E-03
7.0E-04	2.0	7.64E-04	6.99E-07	7.62E-10	9.93E-13	1.15E-07	8.81E-14
7.0E-04	3.0	8.74E-04	1.19E-06	2.55E-09	8.44E-12	4.31E-07	3.26E-12
7.0E-04	5.0	1.13E-03	3.30E-06	2.45E-08	4.38E-10	2.03E-06	3.48E-10
7.0E-04	10.0	1.85E-03	2.20E-05	1.18E-06	1.67E-07	1.86E-05	1.59E-07
7.0E-04	15.0	2.65E-03	7.51E-05	9.56E-06	2.54E-06	6.81E-05	2.45E-06
7.0E-04	20.0	3.50E-03	1.72E-04	3.36E-05	1.18E-05	1.60E-04	1.14E-05
7.0E-04	50.0	8.65E-03	1.47E-03	6.06E-04	3.40E-04	1.40E-03	3.19E-04
7.0E-04	100.0	1.60E-02	4.56E-03	2.43E-03	1.60E-03	4.31E-03	1.45E-03
7.0E-04	150.0	2.19E-02	7.61E-03	4.44E-03	3.09E-03	7.13E-03	2.72E-03
7.0E-04	200.0	2.67E-02	1.04E-02	6.36E-03	4.56E-03	9.65E-03	3.92E-03
1.0E-05	2.0	1.09E-05	1.43E-10	2.22E-15	4.14E-20	2.35E-11	3.66E-21
1.0E-05	3.0	1.25E-05	2.44E-10	7.45E-15	3.55E-19	8.80E-11	1.38E-19
1.0E-05	5.0	1.61E-05	6.78E-10	7.42E-14	2.11E-17	4.18E-10	1.72E-17
1.0E-05	10.0	2.66E-05	5.02E-09	6.58E-12	5.35E-14	4.31E-09	5.28E-14
1.0E-05	15.0	3.88E-05	2.23E-08	1.61E-10	7.81E-12	2.08E-08	7.79E-12
1.0E-05	20.0	5.24E-05	7.20E-08	1.58E-09	1.77E-10	6.92E-08	1.77E-10
1.0E-05	50.0	1.65E-04	3.21E-06	5.67E-07	2.07E-07	3.18E-06	2.06E-07
1.0E-05	100.0	4.37E-04	3.26E-05	1.08E-05	5.47E-06	3.24E-05	5.45E-06
1.0E-05	150.0	7.64E-04	9.60E-05	3.90E-05	2.22E-05	9.54E-05	2.21E-05
1.0E-05	200.0	1.11E-03	1.86E-04	8.36E-05	5.06E-05	1.85E-04	5.02E-05
2.0E-05	2.0	2.18E-05	5.70E-10	1.78E-14	6.62E-19	9.39E-11	5.87E-20
2.0E-05	3.0	2.50E-05	9.76E-10	5.96E-14	5.68E-18	3.52E-10	2.21E-18
2.0E-05	5.0	3.23E-05	2.71E-09	5.94E-13	3.37E-16	1.67E-09	2.74E-16
2.0E-05	10.0	5.33E-05	2.00E-08	5.15E-11	7.56E-13	1.72E-08	7.46E-13
2.0E-05	15.0	7.75E-05	8.79E-08	1.14E-09	8.07E-11	8.19E-08	8.04E-11
2.0E-05	20.0	1.05E-04	2.77E-07	9.73E-09	1.39E-09	2.66E-07	1.39E-09
2.0E-05	50.0	3.24E-04	9.84E-06	2.07E-06	8.17E-07	9.74E-06	8.15E-07
2.0E-05	100.0	8.24E-04	8.08E-05	2.92E-05	1.56E-05	8.02E-05	1.55E-05
2.0E-05	150.0	1.39E-03	2.14E-04	9.28E-05	5.47E-05	2.12E-04	5.42E-05
2.0E-05	200.0	1.97E-03	3.89E-04	1.84E-04	1.15E-04	3.85E-04	1.13E-04
3.0E-05	2.0	3.27E-05	1.28E-09	6.00E-14	3.35E-18	2.11E-10	2.98E-19
3.0E-05	3.0	3.75E-05	2.20E-09	2.01E-13	2.87E-17	7.92E-10	1.12E-17
3.0E-05	5.0	4.84E-05	6.10E-09	2.00E-12	1.70E-15	3.76E-09	1.38E-15
3.0E-05	10.0	7.99E-05	4.50E-08	1.70E-10	3.47E-12	3.86E-08	3.41E-12
3.0E-05	15.0	1.16E-04	1.95E-07	3.50E-09	3.03E-10	1.82E-07	3.01E-10
3.0E-05	20.0	1.57E-04	6.04E-07	2.73E-08	4.46E-09	5.79E-07	4.44E-09
3.0E-05	50.0	4.80E-04	1.86E-05	4.28E-06	1.77E-06	1.83E-05	1.76E-06
3.0E-05	100.0	1.19E-03	1.35E-04	5.13E-05	2.80E-05	1.34E-04	2.78E-05
3.0E-05	150.0	1.95E-03	3.37E-04	1.51E-04	9.09E-05	3.33E-04	8.97E-05
3.0E-05	200.0	2.71E-03	5.88E-04	2.87E-04	1.81E-04	5.81E-04	1.78E-04

S_b

median	ef	m1	m2	m3	m4	variance	covsq
4.0E-05	2.0	4.37E-05	2.28E-09	1.42E-13	1.06E-17	3.76E-10	9.41E-19
4.0E-05	3.0	5.00E-05	3.90E-09	4.76E-13	9.08E-17	1.41E-09	3.54E-17
4.0E-05	5.0	6.45E-05	1.09E-08	4.74E-12	5.37E-15	6.68E-09	4.36E-15
4.0E-05	10.0	1.07E-04	7.98E-08	3.96E-10	1.01E-11	6.85E-08	9.90E-12
4.0E-05	15.0	1.55E-04	3.43E-07	7.67E-09	7.57E-10	3.20E-07	7.52E-10
4.0E-05	20.0	2.09E-04	1.04E-06	5.59E-08	9.97E-09	1.00E-06	9.92E-09
4.0E-05	50.0	6.33E-04	2.88E-05	7.07E-06	3.02E-06	2.84E-05	3.00E-06
4.0E-05	100.0	1.53E-03	1.92E-04	7.56E-05	4.20E-05	1.90E-04	4.16E-05
4.0E-05	150.0	2.48E-03	4.61E-04	2.12E-04	1.29E-04	4.55E-04	1.27E-04
4.0E-05	200.0	3.40E-03	7.75E-04	3.90E-04	2.50E-04	7.63E-04	2.44E-04
7.0E-05	2.0	7.64E-05	6.99E-09	7.63E-13	9.94E-17	1.15E-09	8.83E-18
7.0E-05	3.0	8.74E-05	1.20E-08	2.55E-12	8.51E-16	4.31E-09	3.31E-16
7.0E-05	5.0	1.13E-04	3.32E-08	2.54E-11	5.00E-14	2.05E-08	4.06E-14
7.0E-05	10.0	1.86E-04	2.43E-07	2.02E-09	7.69E-11	2.08E-07	7.54E-11
7.0E-05	15.0	2.71E-04	1.02E-06	3.42E-08	4.28E-09	9.48E-07	4.24E-09
7.0E-05	20.0	3.65E-04	2.99E-06	2.17E-07	4.54E-08	2.86E-06	4.51E-08
7.0E-05	50.0	1.08E-03	6.62E-05	1.82E-05	8.25E-06	6.51E-05	8.17E-06
7.0E-05	100.0	2.48E-03	3.76E-04	1.57E-04	9.05E-05	3.70E-04	8.90E-05
7.0E-05	150.0	3.89E-03	8.35E-04	4.01E-04	2.51E-04	8.20E-04	2.45E-04
7.0E-05	200.0	5.21E-03	1.33E-03	6.97E-04	4.56E-04	1.30E-03	4.42E-04

Table B2: The first four moments, variances and $E[(X_i-\overline{X}_i)^4]$ of the log-normal distribution S_1. (4 Sheets)

S_1

median	ef	m1	m2	m3	m4	variance	covsq
1.0E-01	2.0	1.09E-01	1.43E-02	2.22E-03	4.14E-04	2.32E-03	3.62E-05
1.0E-01	3.0	1.25E-01	2.44E-02	7.44E-03	3.55E-03	8.78E-03	1.38E-03
1.0E-01	5.0	1.61E-01	6.78E-02	7.43E-02	2.12E-01	4.18E-02	1.72E-01
2.0E-01	2.0	2.19E-01	5.71E-02	1.78E-02	6.62E-03	9.28E-03	5.79E-04
2.0E-01	3.0	2.50E-01	9.76E-02	5.95E-02	5.67E-02	3.51E-02	2.21E-02
3.0E-01	2.0	3.28E-01	1.28E-01	6.00E-02	3.35E-02	2.09E-02	2.93E-03
3.0E-01	3.0	3.75E-01	2.20E-01	2.01E-01	2.87E-01	7.90E-02	1.12E-01
4.0E-01	2.0	4.37E-01	2.28E-01	1.42E-01	1.06E-01	3.71E-02	9.26E-03
1.0E-02	2.0	1.09E-02	1.43E-04	2.22E-06	4.14E-08	2.32E-05	3.62E-09
1.0E-02	3.0	1.25E-02	2.44E-04	7.44E-06	3.55E-07	8.78E-05	1.38E-07
1.0E-02	5.0	1.61E-02	6.78E-04	7.43E-05	2.12E-05	4.18E-04	1.72E-05
1.0E-02	10.0	2.66E-02	5.03E-03	6.75E-03	6.42E-02	4.32E-03	6.35E-02
1.0E-02	15.0	3.88E-02	2.26E-02	1.98E-01	2.60E+01	2.11E-02	2.60E+01
1.0E-02	20.0	5.25E-02	7.60E-02	3.03E+00	3.33E+03	7.32E-02	3.33E+03
1.0E-02	50.0	1.69E-01	8.17E+00	1.13E+05	4.46E+11	8.14E+00	4.46E+11
2.0E-02	2.0	2.19E-02	5.71E-04	1.78E-05	6.62E-07	9.28E-05	5.79E-08
2.0E-02	3.0	2.50E-02	9.76E-04	5.95E-05	5.67E-06	3.51E-04	2.21E-06
2.0E-02	5.0	3.23E-02	2.71E-03	5.94E-04	3.39E-04	1.67E-03	2.76E-04
2.0E-02	10.0	5.33E-02	2.01E-02	5.40E-02	1.03E+00	1.73E-02	1.02E+00
2.0E-02	15.0	7.75E-02	9.04E-02	1.58E+00	4.17E+02	8.44E-02	4.16E+02
2.0E-02	20.0	1.05E-01	3.04E-01	2.42E+01	5.33E+04	2.93E-01	5.33E+04
3.0E-02	2.0	3.28E-02	1.28E-03	6.00E-05	3.35E-06	2.09E-04	2.93E-07
3.0E-02	3.0	3.75E-02	2.20E-03	2.01E-04	2.87E-05	7.90E-04	1.12E-05
3.0E-02	5.0	4.84E-02	6.10E-03	2.00E-03	1.71E-03	3.76E-03	1.40E-03
3.0E-02	10.0	7.99E-02	4.53E-02	1.82E-01	5.20E+00	3.89E-02	5.14E+00
3.0E-02	15.0	1.16E-01	2.03E-01	5.34E+00	2.11E+03	1.90E-01	2.11E+03
3.0E-02	20.0	1.57E-01	6.84E-01	8.18E+01	2.70E+05	6.59E-01	2.70E+05
4.0E-02	2.0	4.37E-02	2.28E-03	1.42E-04	1.06E-05	3.71E-04	9.26E-07
4.0E-02	3.0	5.00E-02	3.90E-03	4.76E-04	9.08E-05	1.40E-03	3.53E-05
4.0E-02	5.0	6.46E-02	1.09E-02	4.75E-03	5.42E-03	6.69E-03	4.41E-03
4.0E-02	10.0	1.07E-01	8.05E-02	4.32E-01	1.64E+01	6.92E-02	1.62E+01
4.0E-02	15.0	1.55E-01	3.61E-01	1.27E+01	6.67E+03	3.37E-01	6.66E+03
4.0E-02	20.0	2.10E-01	1.22E+00	1.94E+02	8.53E+05	1.17E+00	8.53E+05
7.0E-02	2.0	7.65E-02	6.99E-03	7.63E-04	9.94E-05	1.14E-03	8.69E-06
7.0E-02	3.0	8.75E-02	1.20E-02	2.55E-03	8.51E-04	4.30E-03	3.31E-04
7.0E-02	5.0	1.13E-01	3.32E-02	2.55E-02	5.08E-02	2.05E-02	4.14E-02
7.0E-02	10.0	1.86E-01	2.47E-01	2.31E+00	1.54E+02	2.12E-01	1.52E+02
1.0E-03	2.0	1.09E-03	1.43E-06	2.22E-09	4.14E-12	2.32E-07	3.62E-13
1.0E-03	3.0	1.25E-03	2.44E-06	7.44E-09	3.55E-11	8.78E-07	1.38E-11
1.0E-03	5.0	1.61E-03	6.78E-06	7.43E-08	2.12E-09	4.18E-06	1.72E-09
1.0E-03	10.0	2.66E-03	5.03E-05	6.75E-06	6.42E-06	4.32E-05	6.35E-06
1.0E-03	15.0	3.88E-03	2.26E-04	1.98E-04	2.60E-03	2.11E-04	2.60E-03
1.0E-03	20.0	5.25E-03	7.60E-04	3.03E-03	3.33E-01	7.32E-04	3.33E-01
1.0E-03	50.0	1.69E-02	8.17E-02	1.13E+02	4.46E+07	8.14E-02	4.46E+07
1.0E-03	100.0	5.03E-02	6.42E+00	2.07E+06	1.69E+15	6.41E+00	1.69E+15
1.0E-03	150.0	1.03E-01	1.14E+02	1.36E+09	1.72E+20	1.14E+02	1.72E+20
1.0E-03	200.0	1.79E-01	1.02E+03	1.88E+11	1.10E+24	1.02E+03	1.10E+24
2.0E-03	2.0	2.19E-03	5.71E-06	1.78E-08	6.62E-11	9.28E-07	5.79E-12
2.0E-03	3.0	2.50E-03	9.76E-06	5.95E-08	5.67E-10	3.51E-06	2.21E-10
2.0E-03	5.0	3.23E-03	2.71E-05	5.94E-07	3.39E-08	1.67E-05	2.76E-08
2.0E-03	10.0	5.33E-03	2.01E-04	5.40E-05	1.03E-04	1.73E-04	1.02E-04
2.0E-03	15.0	7.75E-03	9.04E-04	1.58E-03	4.17E-02	8.44E-04	4.16E-02
2.0E-03	20.0	1.05E-02	3.04E-03	2.42E-02	5.33E+00	2.93E-03	5.33E+00
2.0E-03	50.0	3.38E-02	3.27E-01	9.03E+02	7.13E+08	3.26E-01	7.13E+08
2.0E-03	100.0	1.01E-01	2.57E+01	1.66E+07	2.71E+16	2.57E+01	2.71E+16

S_1

median	ef	m1	m2	m3	m4	variance	covsq
2.0E-03	150.0	2.07E-01	4.58E+02	1.08E+10	2.75E+21	4.58E+02	2.75E+21
2.0E-03	200.0	3.58E-01	4.10E+03	1.50E+12	1.77E+25	4.10E+03	1.77E+25
3.0E-03	2.0	3.28E-03	1.28E-05	6.00E-08	3.35E-10	2.09E-06	2.93E-11
3.0E-03	3.0	3.75E-03	2.20E-05	2.01E-07	2.87E-09	7.90E-06	1.12E-09
3.0E-03	5.0	4.84E-03	6.10E-05	2.00E-06	1.71E-07	3.76E-05	1.40E-07
3.0E-03	10.0	7.99E-03	4.53E-04	1.82E-04	5.20E-04	3.89E-04	5.14E-04
3.0E-03	15.0	1.16E-02	2.03E-03	5.34E-03	2.11E-01	1.90E-03	2.11E-01
3.0E-03	20.0	1.57E-02	6.84E-03	8.18E-02	2.70E+01	6.59E-03	2.70E+01
3.0E-03	50.0	5.07E-02	7.35E-01	3.05E+03	3.61E+09	7.33E-01	3.61E+09
3.0E-03	100.0	1.51E-01	5.77E+01	5.59E+07	1.37E+17	5.77E+01	1.37E+17
3.0E-03	150.0	3.10E-01	1.03E+03	3.66E+10	1.39E+22	1.03E+03	1.39E+22
3.0E-03	200.0	5.37E-01	9.22E+03	5.07E+12	8.94E+25	9.22E+03	8.94E+25
4.0E-03	2.0	4.37E-03	2.28E-05	1.42E-07	1.06E-09	3.71E-06	9.26E-11
4.0E-03	3.0	5.00E-03	3.90E-05	4.76E-07	9.08E-09	1.40E-05	3.53E-09
4.0E-03	5.0	6.46E-03	1.09E-04	4.75E-06	5.42E-07	6.69E-05	4.41E-07
4.0E-03	10.0	1.07E-02	8.05E-04	4.32E-04	1.64E-03	6.92E-04	1.62E-03
4.0E-03	15.0	1.55E-02	3.61E-03	1.27E-02	6.67E-01	3.37E-03	6.66E-01
4.0E-03	20.0	2.10E-02	1.22E-02	1.94E-01	8.53E+01	1.17E-02	8.53E+01
4.0E-03	50.0	6.76E-02	1.31E+00	7.23E+03	1.14E+10	1.30E+00	1.14E+10
4.0E-03	100.0	2.01E-01	1.03E+02	1.33E+08	4.34E+17	1.03E+02	4.34E+17
4.0E-03	150.0	4.14E-01	1.83E+03	8.68E+10	4.40E+22	1.83E+03	4.40E+22
4.0E-03	200.0	7.16E-01	1.64E+04	1.20E+13	2.83E+26	1.64E+04	2.83E+26
7.0E-03	2.0	7.65E-03	6.99E-05	7.63E-07	9.94E-09	1.14E-05	8.69E-10
7.0E-03	3.0	8.75E-03	1.20E-04	2.55E-06	8.51E-08	4.30E-05	3.31E-08
7.0E-03	5.0	1.13E-02	3.32E-04	2.55E-05	5.08E-06	2.05E-04	4.14E-06
7.0E-03	10.0	1.86E-02	2.47E-03	2.31E-03	1.54E-02	2.12E-03	1.52E-02
7.0E-03	15.0	2.71E-02	1.11E-02	6.79E-02	6.25E+00	1.03E-02	6.25E+00
7.0E-03	20.0	3.67E-02	3.72E-02	1.04E+00	8.00E+02	3.59E-02	8.00E+02
7.0E-03	50.0	1.18E-01	4.00E+00	3.87E+04	1.07E+11	3.99E+00	1.07E+11
7.0E-03	100.0	3.52E-01	3.14E+02	7.11E+08	4.07E+18	3.14E+02	4.07E+18
1.0E-04	2.0	1.09E-04	1.43E-08	2.22E-12	4.14E-16	2.32E-09	3.62E-17
1.0E-04	3.0	1.25E-04	2.44E-08	7.44E-12	3.55E-15	8.78E-09	1.38E-15
1.0E-04	5.0	1.61E-04	6.78E-08	7.43E-11	2.12E-13	4.18E-08	1.72E-13
1.0E-04	10.0	2.66E-04	5.03E-07	6.75E-09	6.42E-10	4.32E-07	6.35E-10
1.0E-04	15.0	3.88E-04	2.26E-06	1.98E-07	2.60E-07	2.11E-06	2.60E-07
1.0E-04	20.0	5.25E-04	7.60E-06	3.03E-06	3.33E-05	7.32E-06	3.33E-05
1.0E-04	50.0	1.69E-03	8.17E-04	1.13E-01	4.46E+03	8.14E-04	4.46E+03
1.0E-04	100.0	5.03E-03	6.42E-02	2.07E+03	1.69E+11	6.41E-02	1.69E+11
1.0E-04	150.0	1.03E-02	1.14E+00	1.36E+06	1.72E+16	1.14E+00	1.72E+16
1.0E-04	200.0	1.79E-02	1.02E+01	1.88E+08	1.10E+20	1.02E+01	1.10E+20
2.0E-04	2.0	2.19E-04	5.71E-08	1.78E-11	6.62E-15	9.28E-09	5.79E-16
2.0E-04	3.0	2.50E-04	9.76E-08	5.95E-11	5.67E-14	3.51E-08	2.21E-14
2.0E-04	5.0	3.23E-04	2.71E-07	5.94E-10	3.39E-12	1.67E-07	2.76E-12
2.0E-04	10.0	5.33E-04	2.01E-06	5.40E-08	1.03E-08	1.73E-06	1.02E-08
2.0E-04	15.0	7.75E-04	9.04E-06	1.58E-06	4.17E-06	8.44E-06	4.16E-06
2.0E-04	20.0	1.05E-03	3.04E-05	2.42E-05	5.33E-04	2.93E-05	5.33E-04
2.0E-04	50.0	3.38E-03	3.27E-03	9.03E-01	7.13E+04	3.26E-03	7.13E+04
2.0E-04	100.0	1.01E-02	2.57E-01	1.66E+04	2.71E+12	2.57E-01	2.71E+12
2.0E-04	150.0	2.07E-02	4.58E+00	1.08E+07	2.75E+17	4.58E+00	2.75E+17
2.0E-04	200.0	3.58E-02	4.10E+01	1.50E+09	1.77E+21	4.10E+01	1.77E+21
3.0E-04	2.0	3.28E-04	1.28E-07	6.00E-11	3.35E-14	2.09E-08	2.93E-15
3.0E-04	3.0	3.75E-04	2.20E-07	2.01E-10	2.87E-13	7.90E-08	1.12E-13
3.0E-04	5.0	4.84E-04	6.10E-07	2.00E-09	1.71E-11	3.76E-07	1.40E-11
3.0E-04	10.0	7.99E-04	4.53E-06	1.82E-07	5.20E-08	3.89E-06	5.14E-08
3.0E-04	15.0	1.16E-03	2.03E-05	5.34E-06	2.11E-05	1.90E-05	2.11E-05

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median	ef	m1	m2	m3	m4	variance	covsq
3.0E-04	20.0	1.57E-03	6.84E-05	8.18E-05	2.70E-03	6.59E-05	2.70E-03
3.0E-04	50.0	5.07E-03	7.35E-03	3.05E+00	3.61E+05	7.33E-03	3.61E+05
3.0E-04	100.0	1.51E-02	5.77E-01	5.59E+04	1.37E+13	5.77E-01	1.37E+13
3.0E-04	150.0	3.10E-02	1.03E+01	3.66E+07	1.39E+18	1.03E+01	1.39E+18
3.0E-04	200.0	5.37E-02	9.22E+01	5.07E+09	8.94E+21	9.22E+01	8.94E+21
4.0E-04	2.0	4.37E-04	2.28E-07	1.42E-10	1.06E-13	3.71E-08	9.26E-15
4.0E-04	3.0	5.00E-04	3.90E-07	4.76E-10	9.08E-13	1.40E-07	3.53E-13
4.0E-04	5.0	6.46E-04	1.09E-06	4.75E-09	5.42E-11	6.69E-07	4.41E-11
4.0E-04	10.0	1.07E-03	8.05E-06	4.32E-07	1.64E-07	6.92E-06	1.62E-07
4.0E-04	15.0	1.55E-03	3.61E-05	1.27E-05	6.67E-05	3.37E-05	6.66E-05
4.0E-04	20.0	2.10E-03	1.22E-04	1.94E-04	8.53E-03	1.17E-04	8.53E-03
4.0E-04	50.0	6.76E-03	1.31E-02	7.23E+00	1.14E+06	1.30E-02	1.14E+06
4.0E-04	100.0	2.01E-02	1.03E+00	1.33E+05	4.34E+13	1.03E+00	4.34E+13
4.0E-04	150.0	4.14E-02	1.83E+01	8.68E+07	4.40E+18	1.83E+01	4.40E+18
4.0E-04	200.0	7.16E-02	1.64E+02	1.20E+10	2.83E+22	1.64E+02	2.83E+22
7.0E-04	2.0	7.65E-04	6.99E-07	7.63E-10	9.94E-13	1.14E-07	8.69E-14
7.0E-04	3.0	8.75E-04	1.20E-06	2.55E-09	8.51E-12	4.30E-07	3.31E-12
7.0E-04	5.0	1.13E-03	3.32E-06	2.55E-08	5.08E-10	2.05E-06	4.14E-10
7.0E-04	10.0	1.86E-03	2.47E-05	2.31E-06	1.54E-06	2.12E-05	1.52E-06
7.0E-04	15.0	2.71E-03	1.11E-04	6.79E-05	6.25E-04	1.03E-04	6.25E-04
7.0E-04	20.0	3.67E-03	3.72E-04	1.04E-03	8.00E-02	3.59E-04	8.00E-02
7.0E-04	50.0	1.18E-02	4.00E-02	3.87E+01	1.07E+07	3.99E-02	1.07E+07
7.0E-04	100.0	3.52E-02	3.14E+00	7.11E+05	4.07E+14	3.14E+00	4.07E+14
7.0E-04	150.0	7.24E-02	5.61E+01	4.65E+08	4.12E+19	5.61E+01	4.12E+19
7.0E-04	200.0	1.25E-01	5.02E+02	6.45E+10	2.65E+23	5.02E+02	2.65E+23
1.0E-05	2.0	1.09E-05	1.43E-10	2.22E-15	4.14E-20	2.32E-11	3.62E-21
1.0E-05	3.0	1.25E-05	2.44E-10	7.44E-15	3.55E-19	8.78E-11	1.38E-19
1.0E-05	5.0	1.61E-05	6.78E-10	7.43E-14	2.12E-17	4.18E-10	1.72E-17
1.0E-05	10.0	2.66E-05	5.03E-09	6.75E-12	6.42E-14	4.32E-09	6.35E-14
1.0E-05	15.0	3.88E-05	2.26E-08	1.98E-10	2.60E-11	2.11E-08	2.60E-11
1.0E-05	20.0	5.25E-05	7.60E-08	3.03E-09	3.33E-09	7.32E-08	3.33E-09
1.0E-05	50.0	1.69E-04	8.17E-06	1.13E-04	4.46E-01	8.14E-06	4.46E-01
1.0E-05	100.0	5.03E-04	6.42E-04	2.07E+00	1.69E+07	6.41E-04	1.69E+07
1.0E-05	150.0	1.03E-03	1.14E-02	1.36E+03	1.72E+12	1.14E-02	1.72E+12
1.0E-05	200.0	1.79E-03	1.02E-01	1.88E+05	1.10E+16	1.02E-01	1.10E+16
2.0E-05	2.0	2.19E-05	5.71E-10	1.78E-14	6.62E-19	9.28E-11	5.79E-20
2.0E-05	3.0	2.50E-05	9.76E-10	5.95E-14	5.67E-18	3.51E-10	2.21E-18
2.0E-05	5.0	3.23E-05	2.71E-09	5.94E-13	3.39E-16	1.67E-09	2.76E-16
2.0E-05	10.0	5.33E-05	2.01E-08	5.40E-11	1.03E-12	1.73E-08	1.02E-12
2.0E-05	15.0	7.75E-05	9.04E-08	1.58E-09	4.17E-10	8.44E-08	4.16E-10
2.0E-05	20.0	1.05E-04	3.04E-07	2.42E-08	5.33E-08	2.93E-07	5.33E-08
2.0E-05	50.0	3.38E-04	3.27E-05	9.03E-04	7.13E+00	3.26E-05	7.13E+00
2.0E-05	100.0	1.01E-03	2.57E-03	1.66E+01	2.71E+08	2.57E-03	2.71E+08
2.0E-05	150.0	2.07E-03	4.58E-02	1.08E+04	2.75E+13	4.58E-02	2.75E+13
2.0E-05	200.0	3.58E-03	4.10E-01	1.50E+06	1.77E+17	4.10E-01	1.77E+17
3.0E-05	2.0	3.28E-05	1.28E-09	6.00E-14	3.35E-18	2.09E-10	2.93E-19
3.0E-05	3.0	3.75E-05	2.20E-09	2.01E-13	2.87E-17	7.90E-10	1.12E-17
3.0E-05	5.0	4.84E-05	6.10E-09	2.00E-12	1.71E-15	3.76E-09	1.40E-15
3.0E-05	10.0	7.99E-05	4.53E-08	1.82E-10	5.20E-12	3.89E-08	5.14E-12
3.0E-05	15.0	1.16E-04	2.03E-07	5.34E-09	2.11E-09	1.90E-07	2.11E-09
3.0E-05	20.0	1.57E-04	6.84E-07	8.18E-08	2.70E-07	6.59E-07	2.70E-07
3.0E-05	50.0	5.07E-04	7.35E-05	3.05E-03	3.61E+01	7.33E-05	3.61E+01
3.0E-05	100.0	1.51E-03	5.77E-03	5.59E+01	1.37E+09	5.77E-03	1.37E+09
3.0E-05	150.0	3.10E-03	1.03E-01	3.66E+04	1.39E+14	1.03E-01	1.39E+14
3.0E-05	200.0	5.37E-03	9.22E-01	5.07E+06	8.94E+17	9.22E-01	8.94E+17

S_1

median	ef	m1	m2	m3	m4	variance	covsq
4.0E-05	2.0	4.37E-05	2.28E-09	1.42E-13	1.06E-17	3.71E-10	9.26E-19
4.0E-05	3.0	5.00E-05	3.90E-09	4.76E-13	9.08E-17	1.40E-09	3.53E-17
4.0E-05	5.0	6.46E-05	1.09E-08	4.75E-12	5.42E-15	6.69E-09	4.41E-15
4.0E-05	10.0	1.07E-04	8.05E-08	4.32E-10	1.64E-11	6.92E-08	1.62E-11
4.0E-05	15.0	1.55E-04	3.61E-07	1.27E-08	6.67E-09	3.37E-07	6.66E-09
4.0E-05	20.0	2.10E-04	1.22E-06	1.94E-07	8.53E-07	1.17E-06	8.53E-07
4.0E-05	50.0	6.76E-04	1.31E-04	7.23E-03	1.14E+02	1.30E-04	1.14E+02
4.0E-05	100.0	2.01E-03	1.03E-02	1.33E+02	4.34E+09	1.03E-02	4.34E+09
4.0E-05	150.0	4.14E-03	1.83E-01	8.68E+04	4.40E+14	1.83E-01	4.40E+14
4.0E-05	200.0	7.16E-03	1.64E+00	1.20E+07	2.83E+18	1.64E+00	2.83E+18
7.0E-05	2.0	7.65E-05	6.99E-09	7.63E-13	9.94E-17	1.14E-09	8.69E-18
7.0E-05	3.0	8.75E-05	1.20E-08	2.55E-12	8.51E-16	4.30E-09	3.31E-16
7.0E-05	5.0	1.13E-04	3.32E-08	2.55E-11	5.08E-14	2.05E-08	4.14E-14
7.0E-05	10.0	1.86E-04	2.47E-07	2.31E-09	1.54E-10	2.12E-07	1.52E-10
7.0E-05	15.0	2.71E-04	1.11E-06	6.79E-08	6.25E-08	1.03E-06	6.25E-08
7.0E-05	20.0	3.67E-04	3.72E-06	1.04E-06	8.00E-06	3.59E-06	8.00E-06
7.0E-05	50.0	1.18E-03	4.00E-04	3.87E-02	1.07E+03	3.99E-04	1.07E+03
7.0E-05	100.0	3.52E-03	3.14E-02	7.11E+02	4.07E+10	3.14E-02	4.07E+10
7.0E-05	150.0	7.24E-03	5.61E-01	4.65E+05	4.12E+15	5.61E-01	4.12E+15
7.0E-05	200.0	1.25E-02	5.02E+00	6.45E+07	2.65E+19	5.02E+00	2.65E+19

Table B3: The first four moments, variances and $E[(X_i-\bar{X}_i)^4]$ of the truncated log-normal distribution S_t. (4 Sheets)

S_t

median	ef	m1	m2	m3	m4	variance	covsq
1.0E-01	2.0	1.09E-01	1.43E-02	2.22E-03	4.14E-04	2.34E-03	3.67E-05
1.0E-01	3.0	1.25E-01	2.40E-02	6.89E-03	2.77E-03	8.45E-03	8.46E-04
1.0E-01	5.0	1.49E-01	4.48E-02	2.10E-02	1.27E-02	2.26E-02	4.65E-03
2.0E-01	2.0	2.18E-01	5.70E-02	1.77E-02	6.52E-03	9.33E-03	5.41E-04
2.0E-01	3.0	2.42E-01	8.45E-02	3.95E-02	2.27E-02	2.61E-02	3.91E-03
3.0E-01	2.0	3.26E-01	1.26E-01	5.68E-02	2.95E-02	1.97E-02	1.83E-03
3.0E-01	3.0	3.39E-01	1.55E-01	8.76E-02	5.73E-02	4.00E-02	5.70E-03
4.0E-01	2.0	4.26E-01	2.10E-01	1.18E-01	7.40E-02	2.93E-02	2.92E-03
1.0E-02	2.0	1.09E-02	1.43E-04	2.22E-06	4.14E-08	2.34E-05	3.67E-09
1.0E-02	3.0	1.25E-02	2.44E-04	7.45E-06	3.55E-07	8.79E-05	1.38E-07
1.0E-02	5.0	1.61E-02	6.77E-04	7.15E-05	1.67E-05	4.16E-04	1.29E-05
1.0E-02	10.0	2.59E-02	3.47E-03	1.23E-03	6.72E-04	2.80E-03	5.58E-04
1.0E-02	15.0	3.40E-02	7.03E-03	3.20E-03	1.99E-03	5.87E-03	1.60E-03
1.0E-02	20.0	4.02E-02	1.01E-02	5.09E-03	3.31E-03	8.53E-03	2.59E-03
1.0E-02	50.0	5.72E-02	2.02E-02	1.17E-02	8.16E-03	1.69E-02	5.85E-03
2.0E-02	2.0	2.18E-02	5.71E-04	1.78E-05	6.63E-07	9.38E-05	5.87E-08
2.0E-02	3.0	2.50E-02	9.76E-04	5.96E-05	5.67E-06	3.52E-04	2.21E-06
2.0E-02	5.0	3.22E-02	2.66E-03	5.09E-04	1.81E-04	1.62E-03	1.29E-04
2.0E-02	10.0	4.91E-02	1.01E-02	4.34E-03	2.60E-03	7.65E-03	1.87E-03
2.0E-02	15.0	6.00E-02	1.64E-02	8.30E-03	5.40E-03	1.28E-02	3.73E-03
2.0E-02	20.0	6.70E-02	2.09E-02	1.13E-02	7.59E-03	1.64E-02	5.07E-03
3.0E-02	2.0	3.28E-02	1.28E-03	6.01E-05	3.35E-06	2.11E-04	2.97E-07
3.0E-02	3.0	3.75E-02	2.20E-03	2.01E-04	2.86E-05	7.91E-04	1.11E-05
3.0E-02	5.0	4.82E-02	5.79E-03	1.49E-03	6.36E-04	3.46E-03	4.14E-04
3.0E-02	10.0	6.96E-02	1.75E-02	8.27E-03	5.17E-03	1.27E-02	3.30E-03
3.0E-02	15.0	8.11E-02	2.53E-02	1.35E-02	9.01E-03	1.88E-02	5.49E-03
3.0E-02	20.0	8.77E-02	3.02E-02	1.70E-02	1.16E-02	2.25E-02	6.88E-03
4.0E-02	2.0	4.37E-02	2.28E-03	1.42E-04	1.06E-05	3.75E-04	9.40E-07
4.0E-02	3.0	5.00E-02	3.90E-03	4.75E-04	8.93E-05	1.41E-03	3.41E-05
4.0E-02	5.0	6.39E-02	9.87E-03	3.04E-03	1.45E-03	5.78E-03	8.61E-04
4.0E-02	10.0	8.79E-02	2.51E-02	1.25E-02	8.05E-03	1.74E-02	4.62E-03
4.0E-02	15.0	9.89E-02	3.36E-02	1.85E-02	1.25E-02	2.38E-02	6.89E-03
4.0E-02	20.0	1.05E-01	3.85E-02	2.21E-02	1.53E-02	2.75E-02	8.22E-03
7.0E-02	2.0	7.64E-02	6.99E-03	7.63E-04	9.94E-05	1.15E-03	8.81E-06
7.0E-02	3.0	8.74E-02	1.19E-02	2.49E-03	7.71E-04	4.27E-03	2.70E-04
7.0E-02	5.0	1.09E-01	2.59E-02	1.06E-02	5.91E-03	1.41E-02	2.73E-03
7.0E-02	10.0	1.32E-01	4.68E-02	2.56E-02	1.72E-02	2.93E-02	7.60E-03
1.0E-03	2.0	1.09E-03	1.43E-06	2.22E-09	4.14E-12	2.34E-07	3.67E-13
1.0E-03	3.0	1.25E-03	2.44E-06	7.45E-09	3.55E-11	8.79E-07	1.38E-11
1.0E-03	5.0	1.61E-03	6.79E-06	7.43E-08	2.12E-09	4.18E-06	1.72E-09
1.0E-03	10.0	2.66E-03	4.95E-05	5.19E-06	1.63E-06	4.24E-05	1.57E-06
1.0E-03	15.0	3.86E-03	1.85E-04	4.53E-05	2.20E-05	1.70E-04	2.13E-05
1.0E-03	20.0	5.12E-03	4.26E-04	1.44E-04	8.01E-05	3.99E-04	7.72E-05
1.0E-03	50.0	1.19E-02	2.62E-03	1.32E-03	8.71E-04	2.48E-03	8.11E-04
1.0E-03	100.0	1.88E-02	5.62E-03	3.14E-03	2.16E-03	5.27E-03	1.94E-03
1.0E-03	150.0	2.28E-02	7.60E-03	4.40E-03	3.08E-03	7.08E-03	2.70E-03
1.0E-03	200.0	2.56E-02	9.02E-03	5.32E-03	3.75E-03	8.36E-03	3.24E-03
2.0E-03	2.0	2.18E-03	5.71E-06	1.78E-08	6.63E-11	9.38E-07	5.87E-12
2.0E-03	3.0	2.50E-03	9.76E-06	5.96E-08	5.67E-10	3.52E-06	2.21E-10
2.0E-03	5.0	3.23E-03	2.71E-05	5.94E-07	3.36E-08	1.67E-05	2.73E-08
2.0E-03	10.0	5.32E-03	1.91E-04	3.20E-05	1.27E-05	1.63E-04	1.20E-05
2.0E-03	15.0	7.63E-03	6.20E-04	1.94E-04	1.03E-04	5.61E-04	9.76E-05
2.0E-03	20.0	9.92E-03	1.24E-03	4.89E-04	2.88E-04	1.15E-03	2.69E-04
2.0E-03	50.0	2.01E-02	5.27E-03	2.79E-03	1.87E-03	4.87E-03	1.66E-03
2.0E-03	100.0	2.87E-02	9.46E-03	5.43E-03	3.79E-03	8.64E-03	3.21E-03

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median	ef	m1	m2	m3	m4	variance	covsq
2.0E-03	150.0	3.32E-02	1.19E-02	7.03E-03	4.96E-03	1.08E-02	4.10E-03
2.0E-03	200.0	3.61E-02	1.35E-02	8.11E-03	5.77E-03	1.22E-02	4.70E-03
3.0E-03	2.0	3.28E-03	1.28E-05	6.01E-08	3.35E-10	2.11E-06	2.97E-11
3.0E-03	3.0	3.75E-03	2.20E-05	2.01E-07	2.87E-09	7.92E-06	1.12E-09
3.0E-03	5.0	4.84E-03	6.11E-05	2.00E-06	1.68E-07	3.76E-05	1.36E-07
3.0E-03	10.0	7.97E-03	4.12E-04	8.76E-05	3.83E-05	3.49E-04	3.57E-05
3.0E-03	15.0	1.13E-02	1.21E-03	4.24E-04	2.37E-04	1.08E-03	2.18E-04
3.0E-03	20.0	1.44E-02	2.23E-03	9.42E-04	5.71E-04	2.02E-03	5.19E-04
3.0E-03	50.0	2.69E-02	7.67E-03	4.16E-03	2.82E-03	6.95E-03	2.41E-03
3.0E-03	100.0	3.61E-02	1.25E-02	7.30E-03	5.12E-03	1.12E-02	4.16E-03
3.0E-03	150.0	4.07E-02	1.51E-02	9.05E-03	6.42E-03	1.35E-02	5.09E-03
3.0E-03	200.0	4.35E-02	1.68E-02	1.02E-02	7.29E-03	1.49E-02	5.69E-03
4.0E-03	2.0	4.37E-03	2.28E-05	1.42E-07	1.06E-09	3.75E-06	9.40E-11
4.0E-03	3.0	5.00E-03	3.91E-05	4.76E-07	9.08E-09	1.41E-05	3.54E-09
4.0E-03	5.0	6.46E-03	1.09E-04	4.74E-06	5.20E-07	6.69E-05	4.19E-07
4.0E-03	10.0	1.06E-02	7.04E-04	1.73E-04	8.06E-05	5.92E-04	7.37E-05
4.0E-03	15.0	1.48E-02	1.90E-03	7.16E-04	4.12E-04	1.68E-03	3.72E-04
4.0E-03	20.0	1.87E-02	3.30E-03	1.46E-03	9.02E-04	2.95E-03	8.00E-04
4.0E-03	50.0	3.26E-02	9.85E-03	5.44E-03	3.72E-03	8.79E-03	3.07E-03
4.0E-03	100.0	4.21E-02	1.51E-02	8.90E-03	6.27E-03	1.33E-02	4.92E-03
4.0E-03	150.0	4.66E-02	1.78E-02	1.07E-02	7.64E-03	1.56E-02	5.86E-03
4.0E-03	200.0	4.94E-02	1.95E-02	1.19E-02	8.53E-03	1.71E-02	6.44E-03
7.0E-03	2.0	7.64E-03	6.99E-05	7.63E-07	9.94E-09	1.15E-05	8.81E-10
7.0E-03	3.0	8.75E-03	1.20E-04	2.55E-06	8.52E-08	4.31E-05	3.32E-08
7.0E-03	5.0	1.13E-02	3.32E-04	2.51E-05	4.46E-06	2.05E-04	3.53E-06
7.0E-03	10.0	1.84E-02	1.90E-03	5.94E-04	3.08E-04	1.57E-03	2.68E-04
7.0E-03	15.0	2.49E-02	4.33E-03	1.84E-03	1.11E-03	3.71E-03	9.46E-04
7.0E-03	20.0	3.01E-02	6.70E-03	3.22E-03	2.05E-03	5.79E-03	1.70E-03
7.0E-03	50.0	4.65E-02	1.55E-02	8.81E-03	6.10E-03	1.33E-02	4.65E-03
7.0E-03	100.0	5.58E-02	2.12E-02	1.27E-02	9.05E-03	1.81E-02	6.58E-03
1.0E-04	2.0	1.09E-04	1.43E-08	2.22E-12	4.14E-16	2.34E-09	3.67E-17
1.0E-04	3.0	1.25E-04	2.44E-08	7.45E-12	3.55E-15	8.79E-09	1.38E-15
1.0E-04	5.0	1.61E-04	6.79E-08	7.43E-11	2.12E-13	4.18E-08	1.72E-13
1.0E-04	10.0	2.66E-04	5.03E-07	6.69E-09	5.37E-10	4.32E-07	5.30E-10
1.0E-04	15.0	3.88E-04	2.24E-06	1.47E-07	4.20E-08	2.08E-06	4.17E-08
1.0E-04	20.0	5.25E-04	6.99E-06	1.04E-06	4.32E-07	6.72E-06	4.30E-07
1.0E-04	50.0	1.57E-03	1.54E-04	6.26E-05	3.80E-05	1.52E-04	3.76E-05
1.0E-04	100.0	3.45E-03	6.72E-04	3.37E-04	2.22E-04	6.60E-04	2.17E-04
1.0E-04	150.0	5.05E-03	1.23E-03	6.59E-04	4.46E-04	1.21E-03	4.33E-04
1.0E-04	200.0	6.38E-03	1.75E-03	9.65E-04	6.62E-04	1.71E-03	6.38E-04
2.0E-04	2.0	2.18E-04	5.71E-08	1.78E-11	6.63E-15	9.38E-09	5.87E-16
2.0E-04	3.0	2.50E-04	9.76E-08	5.96E-11	5.67E-14	3.52E-08	2.21E-14
2.0E-04	5.0	3.23E-04	2.71E-07	5.94E-10	3.39E-12	1.67E-07	2.76E-12
2.0E-04	10.0	5.33E-04	2.01E-06	5.24E-08	7.05E-09	1.73E-06	6.94E-09
2.0E-04	15.0	7.76E-04	8.77E-06	9.39E-07	3.30E-07	8.17E-06	3.27E-07
2.0E-04	20.0	1.05E-03	2.58E-05	5.21E-06	2.43E-06	2.47E-05	2.41E-06
2.0E-04	50.0	3.00E-03	3.90E-04	1.72E-04	1.07E-04	3.81E-04	1.05E-04
2.0E-04	100.0	6.01E-03	1.36E-03	7.06E-04	4.72E-04	1.32E-03	4.55E-04
2.0E-04	150.0	8.33E-03	2.25E-03	1.24E-03	8.45E-04	2.18E-03	8.05E-04
2.0E-04	200.0	1.01E-02	3.01E-03	1.70E-03	1.17E-03	2.91E-03	1.11E-03
3.0E-04	2.0	3.28E-04	1.28E-07	6.01E-11	3.35E-14	2.11E-08	2.97E-15
3.0E-04	3.0	3.75E-04	2.20E-07	2.01E-10	2.87E-13	7.91E-08	1.12E-13
3.0E-04	5.0	4.84E-04	6.11E-07	2.01E-09	1.72E-11	3.76E-07	1.40E-11
3.0E-04	10.0	7.99E-04	4.53E-06	1.72E-07	3.00E-08	3.89E-06	2.95E-08
3.0E-04	15.0	1.16E-03	1.93E-05	2.64E-06	1.03E-06	1.80E-05	1.02E-06

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median	ef	m1	m2	m3	m4	variance	covsq
3.0E-04	20.0	1.57E-03	5.41E-05	1.28E-05	6.28E-06	5.17E-05	6.20E-06
3.0E-04	50.0	4.30E-03	6.53E-04	3.00E-04	1.90E-04	6.34E-04	1.85E-04
3.0E-04	100.0	8.10E-03	2.00E-03	1.06E-03	7.14E-04	1.93E-03	6.80E-04
3.0E-04	150.0	1.08E-02	3.14E-03	1.74E-03	1.20E-03	3.02E-03	1.13E-03
3.0E-04	200.0	1.29E-02	4.05E-03	2.31E-03	1.61E-03	3.89E-03	1.49E-03
4.0E-04	2.0	4.37E-04	2.28E-07	1.42E-10	1.06E-13	3.75E-08	9.40E-15
4.0E-04	3.0	5.00E-04	3.91E-07	4.76E-10	9.08E-13	1.41E-07	3.54E-13
4.0E-04	5.0	6.46E-04	1.09E-06	4.75E-09	5.42E-11	6.69E-07	4.41E-11
4.0E-04	10.0	1.07E-03	8.04E-06	3.96E-07	8.16E-08	6.90E-06	7.99E-08
4.0E-04	15.0	1.55E-03	3.35E-05	5.40E-06	2.23E-06	3.11E-05	2.20E-06
4.0E-04	20.0	2.09E-03	9.04E-05	2.36E-05	1.20E-05	8.61E-05	1.18E-05
4.0E-04	50.0	5.54E-03	9.33E-04	4.37E-04	2.79E-04	9.02E-04	2.70E-04
4.0E-04	100.0	1.01E-02	2.60E-03	1.40E-03	9.45E-04	2.50E-03	8.91E-04
4.0E-04	150.0	1.32E-02	3.92E-03	2.21E-03	1.52E-03	3.75E-03	1.41E-03
4.0E-04	200.0	1.55E-02	4.96E-03	2.86E-03	1.99E-03	4.72E-03	1.82E-03
7.0E-04	2.0	7.64E-04	6.99E-07	7.63E-10	9.94E-13	1.15E-07	8.81E-14
7.0E-04	3.0	8.75E-04	1.20E-06	2.55E-09	8.52E-12	4.31E-07	3.32E-12
7.0E-04	5.0	1.13E-03	3.33E-06	2.55E-08	5.08E-10	2.05E-06	4.14E-10
7.0E-04	10.0	1.87E-03	2.45E-05	1.94E-06	5.26E-07	2.10E-05	5.12E-07
7.0E-04	15.0	2.71E-03	9.62E-05	2.02E-05	9.34E-06	8.89E-05	9.12E-06
7.0E-04	20.0	3.62E-03	2.36E-04	7.30E-05	3.93E-05	2.23E-04	3.83E-05
7.0E-04	50.0	8.86E-03	1.78E-03	8.74E-04	5.69E-04	1.70E-03	5.39E-04
7.0E-04	100.0	1.47E-02	4.21E-03	2.32E-03	1.59E-03	3.99E-03	1.46E-03
7.0E-04	150.0	1.84E-02	5.93E-03	3.40E-03	2.37E-03	5.60E-03	2.13E-03
7.0E-04	200.0	2.10E-02	7.21E-03	4.21E-03	2.96E-03	6.77E-03	2.63E-03
1.0E-05	2.0	1.09E-05	1.43E-10	2.22E-15	4.14E-20	2.34E-11	3.67E-21
1.0E-05	3.0	1.25E-05	2.44E-10	7.45E-15	3.55E-19	8.79E-11	1.38E-19
1.0E-05	5.0	1.61E-05	6.79E-10	7.43E-14	2.12E-17	4.18E-10	1.72E-17
1.0E-05	10.0	2.66E-05	5.04E-09	6.75E-12	6.39E-14	4.33E-09	6.32E-14
1.0E-05	15.0	3.88E-05	2.26E-08	1.94E-10	1.72E-11	2.11E-08	1.71E-11
1.0E-05	20.0	5.25E-05	7.57E-08	2.44E-09	5.59E-10	7.30E-08	5.59E-10
1.0E-05	50.0	1.68E-04	4.34E-06	1.23E-06	6.67E-07	4.31E-06	6.67E-07
1.0E-05	100.0	4.56E-04	4.40E-05	1.89E-05	1.17E-05	4.38E-05	1.17E-05
1.0E-05	150.0	7.95E-04	1.19E-04	5.70E-05	3.70E-05	1.18E-04	3.68E-05
1.0E-05	200.0	1.14E-03	2.12E-04	1.07E-04	7.13E-05	2.11E-04	7.08E-05
2.0E-05	2.0	2.18E-05	5.71E-10	1.78E-14	6.63E-19	9.38E-11	5.87E-20
2.0E-05	3.0	2.50E-05	9.76E-10	5.96E-14	5.68E-18	3.52E-10	2.21E-18
2.0E-05	5.0	3.23E-05	2.71E-09	5.94E-13	3.39E-16	1.67E-09	2.76E-16
2.0E-05	10.0	5.33E-05	2.01E-08	5.40E-11	1.01E-12	1.73E-08	9.99E-13
2.0E-05	15.0	7.76E-05	9.04E-08	1.50E-09	2.06E-10	8.43E-08	2.05E-10
2.0E-05	20.0	1.05E-04	3.01E-07	1.66E-08	4.78E-09	2.90E-07	4.77E-09
2.0E-05	50.0	3.33E-04	1.37E-05	4.40E-06	2.48E-06	1.36E-05	2.47E-06
2.0E-05	100.0	8.60E-04	1.06E-04	4.81E-05	3.05E-05	1.06E-04	3.03E-05
2.0E-05	150.0	1.43E-03	2.54E-04	1.26E-04	8.31E-05	2.52E-04	8.23E-05
2.0E-05	200.0	1.97E-03	4.21E-04	2.19E-04	1.47E-04	4.17E-04	1.45E-04
3.0E-05	2.0	3.28E-05	1.28E-09	6.01E-14	3.35E-18	2.11E-10	2.97E-19
3.0E-05	3.0	3.75E-05	2.20E-09	2.01E-13	2.87E-17	7.91E-10	1.12E-17
3.0E-05	5.0	4.84E-05	6.11E-09	2.01E-12	1.72E-15	3.76E-09	1.40E-15
3.0E-05	10.0	7.99E-05	4.53E-08	1.82E-10	5.03E-12	3.89E-08	4.97E-12
3.0E-05	15.0	1.16E-04	2.03E-07	4.90E-09	8.40E-10	1.90E-07	8.38E-10
3.0E-05	20.0	1.58E-04	6.71E-07	4.90E-08	1.58E-08	6.46E-07	1.58E-08
3.0E-05	50.0	4.96E-04	2.60E-05	8.94E-06	5.14E-06	2.57E-05	5.13E-06
3.0E-05	100.0	1.24E-03	1.74E-04	8.09E-05	5.19E-05	1.73E-04	5.15E-05
3.0E-05	150.0	1.99E-03	3.88E-04	1.96E-04	1.30E-04	3.84E-04	1.29E-04
3.0E-05	200.0	2.69E-03	6.16E-04	3.26E-04	2.20E-04	6.09E-04	2.16E-04

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median	ef	m1	m2	m3	m4	variance	covsq
4.0E-05	2.0	4.37E-05	2.28E-09	1.42E-13	1.06E-17	3.75E-10	9.40E-19
4.0E-05	3.0	5.00E-05	3.91E-09	4.76E-13	9.08E-17	1.41E-09	3.54E-17
4.0E-05	5.0	6.46E-05	1.09E-08	4.75E-12	5.42E-15	6.69E-09	4.41E-15
4.0E-05	10.0	1.07E-04	8.06E-08	4.31E-10	1.56E-11	6.92E-08	1.54E-11
4.0E-05	15.0	1.55E-04	3.61E-07	1.12E-08	2.22E-09	3.37E-07	2.21E-09
4.0E-05	20.0	2.10E-04	1.18E-06	1.05E-07	3.61E-08	1.14E-06	3.61E-08
4.0E-05	50.0	6.56E-04	4.04E-05	1.45E-05	8.48E-06	4.00E-05	8.45E-06
4.0E-05	100.0	1.60E-03	2.42E-04	1.16E-04	7.46E-05	2.40E-04	7.39E-05
4.0E-05	150.0	2.52E-03	5.18E-04	2.66E-04	1.77E-04	5.12E-04	1.74E-04
4.0E-05	200.0	3.36E-03	8.00E-04	4.28E-04	2.90E-04	7.89E-04	2.84E-04
7.0E-05	2.0	7.64E-05	6.99E-09	7.63E-13	9.94E-17	1.15E-09	8.81E-18
7.0E-05	3.0	8.75E-05	1.20E-08	2.55E-12	8.52E-16	4.31E-09	3.32E-16
7.0E-05	5.0	1.13E-04	3.33E-08	2.55E-11	5.09E-14	2.05E-08	4.14E-14
7.0E-05	10.0	1.87E-04	2.47E-07	2.31E-09	1.37E-10	2.12E-07	1.36E-10
7.0E-05	15.0	2.72E-04	1.10E-06	5.48E-08	1.37E-08	1.03E-06	1.37E-08
7.0E-05	20.0	3.68E-04	3.52E-06	4.33E-07	1.69E-07	3.39E-06	1.68E-07
7.0E-05	50.0	1.12E-03	9.28E-05	3.61E-05	2.16E-05	9.15E-05	2.14E-05
7.0E-05	100.0	2.57E-03	4.58E-04	2.25E-04	1.47E-04	4.52E-04	1.45E-04
7.0E-05	150.0	3.87E-03	8.89E-04	4.68E-04	3.15E-04	8.74E-04	3.07E-04
7.0E-05	200.0	4.99E-03	1.30E-03	7.10E-04	4.84E-04	1.28E-03	4.70E-04

Table B4: Programme listing of BORO. (4 Sheets)

```
c     ------------------------------------------------
c     programme to evaluate moments  of bounded log-
c     normal distribution
c     ------------------------------------------------
      %global ansi77
      real ef(15),xm(6)
      real fr(7),rj(11)
      data ef/2.0,2.5,3.0,3.3,4.0,5.0,6.0,6.67,8.0,10.0,15.0,20.0,
     &25.0,50.0,100.0/
      data fr/1.e-1,1.e-2,1.e-3,1.e-4,1.e-5,1.e-6,1.e-7/
      data rj/1.0,1.25,1.5,1.67,2.0,2.5,3.0,3.33,4.0,5.0,7.0/
      data nl/1/
      call prt(nl)
      do 9 jj=1,5
      do 10 i=1,11
      xr=rj(i)*fr(jj)
      do 20 j=1,15
      call conv(xr,ef(j),xlm,xls)
      if(xlm.eq.0.0.or.xls.eq.0.0) go to 10
      do 30 k=1,4
      xm(k)=xmom(k,xlm,xls)
   30 continue
      xm(5)=xm(2)-xm(1)**2
      xm(6)=xm(4)-4.*xm(3)*xm(1)+6.*xm(2)*xm(1)**2-3.*xm(1)**4
      write(6,100)xr,ef(j),(xm(ii),ii=1,6)
  100 format(1h ,1pe8.1,0pf6.1,t16,6(1pe10.2))
      nl=nl+1
      if(nl.gt.55) call prt(nl)
   20 continue
   10 continue
 9    continue
      stop
      end
      subroutine conv(xmed,xef,xlm,xls)
c     ------------------------------------------------
c     routine to calculate log mean and log deviation
c     ------------------------------------------------
      if(xef.le.1.0) goto 100
      x95=xmed*xef
      if(x95.ge.1.0) goto 100
      xlm=alog(xmed/(1.0-xmed))
      xls=(alog(x95/(1.0-x95))-xlm)/1.645
      return
  100 xlm=0.0
      xls=0.0
      return
      end
      function xjb(x,xlm,xls)
c     ------------------------------------------------
c     routine to calculate bounded log-normal pdf
c     ------------------------------------------------
      data pi/3.141592654/
      if(x.le.0.0.or.x.ge.1.0) go to 100
      y=(alog(x/(1.-x))-xlm)**2/(-2.*xls**2)
      if(y.lt.-60.0) go to 100
      xjb=exp(y)/(x*(1.-x)*xls*(2.*pi)**.5)
      return
  100 xjb=0.0
      return
      end
```

```
      function xmom(m,xlm,xls)
c     ------------------------------------------------
c     routine to calculate the m th moment
c     ------------------------------------------------
      flag=0.0
      tot=0.0
      gb=2.575
      n=100
      a=xlm+gb*xls
      xu=1.0
      b=xlm-gb*xls
      xl=exp(b)/(1.+exp(b))
      xm=xmode(m,xlm,xls)
      if(xm.ge.1.0) go to 100
      if(xl.ge.xm) go to 200
      xn=n/(m+2)
      nh1=ifix(xn)
      nh2=n-nh1
      go to 13
 200  flag=2.0
      nh1=n
      xm=exp(a)/(1.+exp(a))
 13   h1=(alog10(xu)-alog10(xm))/nh1
      do 10 i=1,nh1
      if(i.eq.1) then
      x1=xm
      f1=(x1**m)*xjb(x1,xlm,xls)
      else
      x1=x3
      f1=f3
      end if
      x3=10.**(alog10(xm)+i*h1)
      xt=xjb(x3,xlm,xls)
      x2=(x1+x3)/2.
      xd=abs(x3-x1)/2.0
      f2=(x2**m)*xjb(x2,xlm,xls)
      f3=(x3**m)*xt
      tot=tot+xd*(f1+4.*f2+f3)/3.
 10   continue
 21   if(flag.eq.2.0) go to 30
      go to 23
 100  xm=1.0
      nh2=n
 23   h1=(alog10(xm)-alog10(xl))/nh2
      do 20 i=1,nh2
      if(i.eq.1) then
      x1=xm
      f1=(x1**m)*xjb(x1,xlm,xls)
      else
      x1=x3
      f1=f3
      end if
      xt=xjb(x1,xlm,xls)
      x3=10.**(alog10(xm)-i*h1)
      xt=xjb(x3,xlm,xls)
      x2=(x1+x3)/2.
      xd=abs(x1-x3)/2.
      f2=(x2**m)*xjb(x2,xlm,xls)
      f3=(x3**m)*xt
      tot=tot+xd*(f1+4.*f2+f3)/3.
```

```
 20   continue
 30   xmom=tot
      return
      end
      function xmode(m,xlm,xls)
c     ------------------------------------------------
c     routine to find the maximum of the function
c     g(x)=(x**m)*f(x) by solving g'(x)=0 using
c     the Newton-Raphson's method
c     ------------------------------------------------
      if(m.eq.0) go to 300
      xlimit=1.0e-15
      n=50
      epa=1.0e-6
      xlv=xls**2
      xg=exp(xlm+(m-1)*xlv)
      if(xg.ge.1.0) xg=.999999
      hlimit=xg*1.0e-6
      yt=fx(xg,m,xlm,xlv)
      do 10 i=1,n
      h=-yt/dfx(xg,m,xlm,xlv)
      if(h.le.hlimit) go to 100
      xg=xg+h
      if(xg.ge.1.0.or.xg.le.0.0) xg=.999999
      yt2=fx(xg,m,xlm,xlv)
      if(abs(yt2).lt.xlimit) go to 100
      ct=(yt-yt2)/yt
      if(abs(ct).le.epa) go to 100
      yt=yt2
 10   continue
      err=2.0
      xmode=xg
      n=i
      return
 100  err=0.0
      xmode=xg
      n=i
      return
 200  err=1.0
      xmode=xg
      n=i
      return
 300  err=0.0
      xmode=exp(xlm)/(1.+exp(xlm))
      n=0
      return
      end
      function fx(x,m,xlm,xlv)
c     ------------------------------------------
c     first derivative of the function
c     g(x)=(x**m)*f(x)
c     ------------------------------------------
      if(x.le.0.0.or.x.ge.1.0) go to 100
      fx=alog(x/(1.-x))+(m-2)*xlv*x-(m-1)*xlv-xlm
      return
 100  fx=0.0
      return
      end
      function dfx(x,m,xlm,xlv)
c     ------------------------------------------
```

```
c       second derviative of the function
c       g(x)=(x**m)*f(x)
c       ---------------------------------------------
        if(x.le.0.0.or.x.gt.1.0) go to 100
        dfx=1./(x*(1.-x))+(m-2)*xlv
        return
 100    dfx=0.0
        return
        end
        subroutine prt(nl)
c       ---------------------------------------------
c       routine to print page heading
c       ---------------------------------------------
        data np/1/
        write(6,100)np
 100    format(1h1,t72,'page:',i3)
        write(6,200)
 200    format(1h ,' median ',3x,'ef',t20,'m1',8x,'m2',8x,'m3',8x,
       &'m4',6x,'variance',3x,'covsq')
        nl=1
        np=np+1
        return
        end
```

Table B5: Programme listing of LORO (2 Sheets).

```
c     ------------------------------------------------
c     programme to evaluate moments  of log-
c     normal distribution
c     ------------------------------------------------
      %global ansi77
      real ef(10),xm(6)
      real fr(7),rj(5)
      data ef/2.0,3.0,5.0,10.0,15.0,20.0,50.0,100.0,150.0,200.0/
      data rj/1.0,2.0,3.0,4.0,7.0/
      data nl/1/
      data fr/1.0e-1,1.0e-2,1.0e-3,1.0e-4,1.0e-5,1.0e-6,1.0e-7/
      call prt(nl)
      do 9 jj=1,5
      do 10 i=1,5
      xr=rj(i)*fr(jj)
      do 20 j=1,10
      call conv(xr,ef(j),xlm,xls)
      if(xlm.eq.0.0.or.xls.eq.0.0) go to 10
      do 30 k=1,4
      xm(k)=xmom(k,xlm,xls)
   30 continue
      xm(5)=xm(2)-xm(1)**2
      xm(6)=xm(4)-4.*xm(3)*xm(1)+6.*xm(2)*xm(1)**2-3.*xm(1)**4
      write(6,100)xr,ef(j),(xm(ii),ii=1,6)
  100 format(1h ,1pe8.1,0pf6.1,t16,6(1pe10.2))
      nl=nl+1
      if(nl.gt.55) call prt(nl)
   20 continue
   10 continue
    9 continue
      stop
      end
      subroutine conv(xmed,xef,xlm,xls)
c     ------------------------------------------------
c     routine to calculate log mean and log deviation
c     ------------------------------------------------
      if(xef.le.1.0) goto 100
      x95=xmed*xef
      if(x95.ge.1.0) goto 100
      xlm=alog(xmed)
      xls=alog(xef)/1.645
      return
  100 xlm=0.0
      xls=0.0
      return
      end
      function xjb(x,xlm,xls)
c     ------------------------------------------------
c     routine to calculate  log-normal pdf
c     ------------------------------------------------
      data pi/3.141592654/
      if(x.le.0.0) go to 100
      y=(alog(x)-xlm)**2/(-2.*xls**2)
      if(y.lt.-87.2) go to 100
      xjb=exp(y)/(x*xls*(2.*pi)**.5)
      return
  100 xjb=0.0
      return
      end
      function xmom(m,xlm,xls)
```

```
c     ---------------------------------------------------
c     routine to calculate the m th moment
c     ---------------------------------------------------
      y=(m*xlm+(m*xls)**2*.5)
      if(y.lt.-87.2) then
      xmom=0.0
      else
      xmom=exp(y)
      end if
      return
      end
      subroutine prt(nl)
c     ---------------------------------------------
c     routine to print page heading
c     ---------------------------------------------
      data np/1/
      write(6,100)np
 100  format(1h1,t72,'page: ',i3)
      write(6,200)
 200  format(1h ,' median ',2x,'ef',t20,'m1',8x,'m2',8x,'m3',8x,
     &'m4',5x,'variance',4x,'covsq')
      nl=1
      np=np+1
      return
      end
```

Table B6: Programme listing of TORO (4 Sheets)

```
c     ------------------------------------------------
c     programme to evaluate moments  of truncated log-
c     normal distribution
c     ------------------------------------------------
      %global ansi77
      real ef(13),xm(6)
      real fr(7),rj(12)
      data ef/2.0,2.5,3.0,3.33,4.0,5.0,6.0,6.67,10.0,15.0,20.0,50.0,
     &100.0/
      data fr/1.e-1,1.e-2,1.e-3,1.e-4,1.e-5,1.e-6,1.e-7/
      data rj/1.0,1.25,1.5,2.0,2.5,3.0,3.33,4.0,5.0,6.0,6.67,7.0/
      data nl/1/
      call prt(nl)
      do 9 jj=1,5
      do 10 i=1,12
      xr=rj(i)*fr(jj)
      do 20 j=1,13
      call conv(xr,ef(j),xlm,xls,c)
      if(xlm.eq.0.0.or.xls.eq.0.0) go to 10
      do 30 k=1,4
      xm(k)=xmom(k,xlm,xls,c)
   30 continue
      xm(5)=xm(2)-xm(1)**2
      xm(6)=xm(4)-4.*xm(3)*xm(1)+6.*xm(2)*xm(1)**2-3.*xm(1)**4
      write(6,100)xr,ef(j),(xm(ii),ii=1,6)
  100 format(1h ,1pe8.1,0pf6.1,t16,6(1pe10.2))
      nl=nl+1
      if(nl.gt.55) call prt(nl)
   20 continue
   10 continue
 9    continue
      stop
      end
      subroutine conv(xmed,xef,xlm,xls,c)
c     ------------------------------------------------
c     routine to calculate log mean and log deviation
c     ------------------------------------------------
      if(xef.le.1.0) goto 100
      x95=xmed*xef
      if(x95.ge.1.0) goto 100
      xlm=alog(xmed)
      xls=alog(xef)/1.645
      m=0
      c=factor(xlm,xls)
      return
  100 xlm=0.0
      xls=0.0
      return
      end
      function xjb(x,xlm,xls)
c     ------------------------------------------------
c     routine to calculate truncated log-normal pdf
c     ------------------------------------------------
      data pi/3.141592654/
      if(x.le.0.0.or.x.gt.1.0) go to 100
      y=(alog(x)-xlm)**2/(-2.*xls**2)
      if(y.lt.-60.0) go to 100
      xjb=exp(y)/(x*xls*(2.*pi)**.5)
      return
  100 xjb=0.0
```

```
      return
      end
      function factor(xlm,xls)
c     ---------------------------------------------------
c     routine to calculate the normalization factor
c     ---------------------------------------------------
      tot=0.0
      n=100
      gb=3.5
      a=xlm+gb*xls
      b=xlm-gb*xls
      xl=exp(b)
      xu=exp(a)
      xm=exp(xlm)
      if(xu.gt.1.0)xu=1.0
      nh2=n/4
      nh1=n-nh2
      hl=(alog10(xu)-alog10(xm))/nh1
      do 10 i=1,nh1
      if(i.eq.1)then
      x1=xm
      f1=xjb(x1,xlm,xls)
      else
      x1=x3
      f1=f3
      end if
      x3=10.**(alog10(xm)+i*hl)
      x2=(x1+x3)/2.0
      xd=abs(x3-x1)/2.0
      f2=xjb(x2,xlm,xls)
      f3=xjb(x3,xlm,xls)
      tot=tot+xd*(f1+4.*f2+f3)/3.0
 10   continue
      hl=(alog10(xm)-alog10(xl))/nh2
      do 20 i=1,nh2
      if(i.eq.1) then
      x1=xm
      f1=xjb(x1,xlm,xls)
      else
      x1=x3
      f1=f3
      end if
      x3=10.**(alog10(xm)-i*hl)
      x2=(x1+x3)/2.0
      xd=abs(x1-x3)/2.0
      f2=xjb(x2,xlm,xls)
      f3=xjb(x3,xlm,xls)
      tot=tot+xd*(f1+4.*f2+f3)/3.0
 20   continue
      factor=tot
      return
      end
      function xmom(m,xlm,xls,c)
c     ---------------------------------------------------
c     routine to calculate the m th moment
c     ---------------------------------------------------
      flag=0.0
      tot=0.0
      n=100
      nh2=n/2
```

```
      nh1=n-nh2
      gb=2.575
      a=xlm+gb*xls
      b=xlm-gb*xls
      if(m.eq.0) go to 50
      xu=1.0
      xl=exp(b)
      xm=exp(xlm+(m-1)*xls**2)
      if(xl.ge.xm)go to 60
      if(xm.ge.xu)go to 70
      go to 13
50    xm=exp(xlm)
      xu=exp(a)
      xl=exp(b)
      go to 13
60    flag=2.0
      xu=1.0
      xm=exp(a)
      nh1=n
      go to 13
70    xm=1.0
      xl=exp(b)
      nh2=n
      go to 23
13    hl=(alog10(xu)-alog10(xm))/nh1
      do 10 i=1,nh1
      if(i.eq.1) then
      x1=xm
      f1=(x1**m)*xjb(x1,xlm,xls)
      else
      x1=x3
      f1=f3
      end if
      x3=10.**(alog10(xm)+i*hl)
      xt=xjb(x3,xlm,xls)
      x2=(x1+x3)/2.
      xd=abs(x3-x1)/2.0
      f2=(x2**m)*xjb(x2,xlm,xls)
      f3=(x3**m)*xt
      tot=tot+xd*(f1+4.*f2+f3)/3.
10    continue
21    if(flag.eq.2.0) go to 30
23    hl=(alog10(xm)-alog10(xl))/nh2
      do 20 i=1,nh2
      if(i.eq.1) then
      x1=xm
      f1=(x1**m)*xjb(x1,xlm,xls)
      else
      x1=x3
      f1=f3
      end if
      x3=10.**(alog10(xm)-i*hl)
      xt=xjb(x3,xlm,xls)
      x2=(x1+x3)/2.
      xd=abs(x1-x3)/2.
      f2=(x2**m)*xjb(x2,xlm,xls)
      f3=(x3**m)*xt
      tot=tot+xd*(f1+4.*f2+f3)/3.
 20   continue
30    xmom=tot/c
```

```
      return
      end
      subroutine prt(nl)
c     ---------------------------------------------
c     routine to print page heading
c     ---------------------------------------------
      data np/1/
      write(6,100)np
 100  format(1h1,t72,'page: ',i3)
      write(6,200)
 200  format(1h ,' median ',3x,'ef ',t20,'m1 ',8x,'m2 ',8x,'m3 ',8x,
     &'m4 ',6x,'variance ',3x,'covsq ')
      nl=1
      np=np+1
      return
      end
```

APPENDIX C: Automatic Pressure Relief System Description

APPENDIX C: Automatic Pressure Relief System (APR) Description

C.1.1 Purpose

The purpose of the automatic pressure relief (APR) system is to provide a backup method for reducing reactor pressure rapidly in the event of feedwater coolant injection system failure. Since each of the four APR valves also functions as a safety valve, they are additionally able to prevent the reactor vessel pressure safety limit of 1375 psig from being exceeded. All together, there are six valves that perform this safety/relief valve function.

C.1.2 Description and Configuration

The four APR valves are considered dual purpose since they are self-actuating at the set relieving pressure and are air operated at pressures below the setpoint, which permits remote manual or automatic opening.

The dual valve consists of two main sections (see Figure C.1). The pilot valve section is a relatively small self-actuated relief valve, integral with the main valve, which provides pressure sensing and main valve control functions. The main element of this pilot valve is a precision machined spring-bellows, the expansion of which accurately controls pilot valve opening pressure. The main relief-safety valve section is a hydraulically-operated, reverse-seated globe valve which, when actuated by the pilot valve via the second stage disk, provides the pressure relief function. Thus, the four APR valves are capable of functioning (see Figure C.2) as safety/relief valves opening automatically at the following setpoints:

1) APR valve MS-3A opens at 1095 psig
2) APR valve MS-3D opens at 1110 psig
3) APR valves MS-3C and MS-3F open at 1125 psig

In addition, the two remaining safety/relief valves which are not capable of automatic remote actuation open at 1125 psig.

When the APR valves operate in the remote actuation mode, the air operator performs the function of the pilot valve section, causing the second stage disk to open. This results in main valve actuation, as shown in Figure C.2 , similar to the safety mode except here the pilot valve remains closed.

The APR system is capable of operation without reliance on off-site power or station air. Control power to the air operator solenoid is supplied by redundant 125 volt DC power sources, and sufficient air is stored in emergency accumulators for several valve cycling operations.

APR valves MS-3A, 3C, 3D, and 3F are located on horizontal sections of main steam lines A, C, B, and D, respectively. The two safety/relief valves MS-3B and 3E are similarly installed on steam lines B and C. Each valve discharge is piped through its own discharge line to a point below the water level in the primary containment suppression pool (torus) to permit steam to condense in the pool. Each exhaust line is equipped with a vacuum relief valve to prevent drawing water up into the line due to steam condensation following termination of operation.

C.1.3 System Interfaces

See attached Table C.1

C.1.4 Instrumentation and Control

Automatic actuation of the APR system requires coincident indication of reactor water lo-lo level and high drywell pressure, as well as persistance of the lo-lo water level signal for two minutes. An interlock prevents actuation of the APR function until the discharge pressure of at least one LPCI or core spray pump exceeds 100 psig. This ensures that the system will not

operate until the low pressure ECCS pumps are running. System instrumentation is listed in Table

The actuation logic consists of two redundant trip systems, either of which is capabale of initiating auto blowdown upon receipt of the accident signal. Each of these trip systems is further divided into two trip logic channels. Both channels within a given trip system must actuate in order to initiate the trip system logic. A channel consists of lo-lo reactor water level instrumentation, high drywell pressure instrumentation and an a ECCS "pump running" interlock, all in series with each other. Since every core spray and LPCI pump has two pressure switches on its discharge side, each switch acts as an interlock on one of the two trip channels.

A time delay circuit is located in series with one of the trip logic channels in each trip system to allow time for the FWCI system to achieve proper operation. If the FWCI system maintains water level in the reactor vessel, the blowdown circuit is de-energized and the automatic blowdown signal is blocked. If, however, the FWCI system fails to deliver sufficient flow, the blowdown actuates upon termination of the time delay (two minutes). The APR system initiation logic is shown in Figure

The time delay also provides surveillance time so that the operator can evaluate possible spurious activation signals and override them if necessary. A permissive signal from the time delay circuit serves as the confirming signal to activate the APR valves when the control station switch is in the automatic position. Manual blowdown of the reactor vessel is accomplished independently of the automatic circuitry.

The automatic pressure relief system is provided with redundant power supplies to each auto-relief valve and auto

blowdown trip system. Upon loss of the primary DC power supply to these circuits, automatic transfer to an alternate DC power supply will be accomplished. Hence, the pressure relief system will be maintained for both manual and automatic operation in the event that a station battery is lost.

C.1.5 Testing

There are two primary tests of the APR system, SP 413B and SP 413C, which are conducted during each refueling outage (approximately every 12,000 hours), and three related tests which are performed monthly to check the function and calibration of the accident detection instrumentation. Bench testing of the safety/relief valves is performed during each refueling outage, and functional tests are performed at normal and low reactor operating pressures.

SP 413B Auto Blowdown Logic Test

One of the objectives of this test is to verify the logic sequence of the automatic blowdown (APR) system by simulated auto-initiation. A simulated accident signal is placed separately on each of the four trip logic channels (two channels per trip system). The test is considered to be satisfactory if each channel actuates as required. In addition, the two trip channels having time delay circuits must actuate a "blowdown" at or less than 120 seconds from initiation.

The other objective of this test is to verify auto-transfer of DC control power to the alternate source upon loss of the primary. Fuses are pulled on the primary DC power supply and successful transfer to the alternate supply, along with control room panel

annunciation is checked. This test is performed on both auto-blowdown trip system power supplies as well as each auto-relief valve solenoid power supply.

SP 413C Automatic Actuation of Automatic Pressure Relief Subsystem

The objective of this test is to verify that a simulated auto-initiation signal will open all four APR valve solenoids. A simulated accident signal is placed on both trip logic channels of trip system "A". A successful test occurs if after 120 seconds the green APR indicating lights on control room panel 903 go out and the red indicating light comes on, indicating power to the APR actuation solenoid.

SP 413A LP Core Cooling Pump Interlock Functional and Calibration Test

The objective of this monthly test is to check the function of the LPCI and core spray pump interlock pressure sensors, and calibrate them if necessary. The test is considered to be satisfactorily completed provided the switches trip at 100 psig (± 10 psig).

SP 412C Reactor Low Low Water Level Functional and Calibration Test

The objective of this monthly test is to determine if the four water level switches (as listed in Table C.2) will trip at the setpoint of 79" above the top of the active fuel, and to calibrate them if necessary.

SP 412D High Drywell Pressure Functional and Calibration Test

The objective of this monthly test is to demonstrate that the four drywell pressure detection switches (as

listed in Table C.2) will trip at a pressure less than or equal to 2 psig.

SP 626.2 Manual Operation of Relief Valves When at Low Pressure

Once during each refueling cycle each safety/relief valve must be manually operated while the reactor is at low pressure.

SP 626.3 Manual Operation of Relief Valves when at Operating Pressure

The safety/relief valves are to be opened, one at a time, while the reactor is at operating pressure. There is no set interval for the performance of this test.

SP 778.1 Inspection of Safety/Relief Valves

During each refueling outage one safety/relief valve is disassembled and inspected.

SP 778.2 Bench Check of Safety/Relief Valves

During each refueling outage three of the six safety/relief valves "top works" are bench tested. All six valves are tested during a span of two refuelings.

C.1.6 Maintenance

The four APR valves and the two safety/relief valves are maintained in accordance with the surveillance requirements spelled out by the Technical Specifications. At each refueling outage, three of the six valves have their "top works" either bench checked or replaced with bench checked "top works," so that all six valves are maintained by the end of two refueling outages (approx. 24,000 hours). In addition, at least one of the six valves is disassembled and inspected during each refueling outage

so that all of the valves will be overhauled by the end of six refueling outages, at most.

C.1.7 Technical Specifications

The limiting conditions for operation require that all six safety/relief valves be operable in the safety valve mode whenever reactor pressure and temperature are greater than 90 psig and 320°F, respectively. Failure of any one valve to operate in this mode (as a safety valve) mandates cold shutdown within 24 hours. The same limiting condition for operation applies to the four safety/relief valves functioning in the automatic pressure relief mode, with the following exception. Reactor operation is allowed for a period of 7 days with one of the APR valves inoperable, provided that the remaining APR valves, the FWCI system and the gas turbine generator are all operable. If the inoperable APR valve cannot be repaired within that time, the reactor is required to be in cold shutdown as stated earlier.

The surveillance requirements similarly address the dual function of the six safety/relief valves. All six valves must be opened manually, with the reactor at low pressure, once during each operating cycle to demonstrate operability in the safety valve mode. Additional surveillance requirements regarding valve maintenance have already been discussed in the preceding section, C.1.6 .

Surveillance of the four APR valves includes all of the requirements stated for the safety valve mode. Additionally, during each operating cycle a simulated automated initiation of the system, excluding actual valve opening, is performed. Also, if one APR valves is found to be inoperable, the actuation logic of the remaining APR valves, the FWCI system, and the gas turbine generator must be demonstrated to be operable on a daily basis.

C.1.8 Operation

The APR system operates automatically to depressurize the reactor whenever the FWCI system is unable to maintain proper vessel water inventory under accident conditions. The system is actuated upon indication of high drywell pressure coincident with a 120 second persistant low reactor water level signal, and if at least one LPCI or core spray pump is running.

If the APR control switch is not in the automatic position or if there is a failure in the automatic actuation logic, the system can be operated manually from the 903 control room panel. Each of the four safety/relief valves that operates in the remote automatic actuation mode is clearly identified by a large "APR" label under its control switch. Next to the control switch layout is another label which keys the operator to the manual relief valve opening sequence. Unlike the remote automatic actuation mode all six saftey/relief valves may be opened manually. Actual APR valve opening has already been discussed in section

C.2 Analysis

C.2.1 Success/Failure Criteria

Three modes of operation were considered for the safety/relief valves. A fault tree was constructed for the APR system which utilizes four of the six safety/relief valves. Additionally, the pressure relief function and manual depressurization operation were examined.

Successful operation of the APR system requires that two out of the four APR valves operate to blowdown the reactor vessel when required to do so. Loss of two of the relief valves does not materially affect the pressure relieving capability.

System failure occurs whenever three of the four APR valves fail to open when demanded. However, since all six safety/relief valves can be remotely operated by the reactor operator, five out of six would have to fail if manual recovery were considered.

To perform the pressure relief function four of the six safety/relief valves must open to relieve reactor vessel pressure. Failure of three of the four valves was analyzed and it was determined that the system failure probability was sufficiently negligable.

Failure of the system in the manual depressurization mode, requiring that three of the six safety/relief valves do not open, is dominated by operator failure to initiate manual depressurization. A THERP analysis has been performed for this event.

Table C.2 Component Unavailability Data (11 Sheets)

FAULT SUMMARY SHEETS

EVENT	DESCRIPTION	DETECTION INTERVAL	COMMENTS	UNAVAILABILITY
MS-3A-PHV-FTO MS-3C-PHV-FTO MS-3D-PHV-FTO MS-3F-PHV-FTO	APR valve fails to open	12000 hrs (detected during refueling outages)	Tested as per SP 626.2	$1x10^{-3}$
2Ø3-3A-FTE 2Ø3-3C-FTE 2Ø3-3D-FTE 2Ø3-3F-FTE	APR valve solenoid fails to energize	12000 hrs (detected during refueling outages)	Tested when valve cycled in SP 626.2	$1.7x10^{-3}$
2Ø3-3A-SOV-FTO 2Ø3-3C-SOV-FTO 2Ø3-3D-SOV-FTO 2Ø3-3F-SOV-FTO	Solenoid operated air valve fails to open	12000 hrs (detected during refueling outages)	Tested when valve cycled in SP 626.2	$1.7x10^{-2}$
932287-1Ø9A-2RC 932287-1Ø9C-2RC 932287-1Ø9D-2RC 932287-1Ø9F-2RC 932287-1Ø9A-1RC 932287-1Ø9C-1RC 932287-1Ø9D-1RC 932287-1Ø9F-1RC	Relay contacts fail to remain closed	12000 hrs (detected during refueling outages)	Auto actuation of APR subsystem as per SP 413B	$6x10^{-4}$
932287-1Ø9A-FRE 932287-1Ø9C-FRE 932287-1Ø9D-FRE 932287-1Ø9F-FRE	Failure of relay coil to remain energized	12000 hrs (detected during refueling outages)	Auto blowdown logic test as per SP 413B	$6x10^{-4}$

MILLSTONE 1
SYSTEM APR
SHEET #1

FAULT SUMMARY SHEETS

EVENT	DESCRIPTION	DETECTION INTERVAL	COMMENTS	UNAVAILABILITY
287-7Ø3A-FUS-LOF 287-7Ø3C-FUS-LOF 287-7Ø3D-FUS-LOF 287-7Ø3F-FUS-LOF 287-7Ø4A-FUS-LOF 287-7Ø4C-FUS-LOF 287-7Ø4D-FUS-LOF 287-7Ø4F-FUS-LOF	Failure of fuses on DC power supply	Prompt	"Fuse Monitor" annunciator on CRP 903 alerts operators	2.4×10^{-5}
DC-11A2-21-FRC	Local faults on breaker	Prompt	Annunciated in the control room	2.4×10^{-5}
932287-1Ø9A-3FC 932287-1Ø9C-3FC 932287-1Ø9D-3FC 932287-1Ø9F-3FC 932287-1Ø9A-4FC 932287-1Ø9C-4FC 932287-1Ø9D-4FC 932287-1Ø9F-4FC	Relay contacts fail to close	12000 hrs (detected during refueling outages)	Auto blowdown logic test as per SP 413B	1.8×10^{-3}
287-7Ø7A-FUS-LOF 287-7Ø7C-FUS-LOF 287-7Ø7D-FUS-LOF 287-7Ø7F-FUS-LOF 287-7Ø8A-FUS-LOF 287-7Ø8C-FUS-LOF 287-7Ø8D-FUS-LOF 287-7Ø8F-FUS-LOF	Failure of fuses on alt. D.C. supply	12000 hrs (detected during refueling outages)	Auto blowdown logic test as per SP 413B	6×10^{-3}

MILLSTONE 1
SYSTEM APR
SHEET #2

FAULT SUMMARY SHEETS

EVENT	DESCRIPTION	DETECTION INTERVAL	COMMENTS	UNAVAILABILITY
932287-1Ø6A-FTE 932287-1Ø5A-FTE 932287-1Ø4A-FTE 932287-1Ø3A-FTE	Relay coil fails to energize	12000 hrs (detected during refueling outages)	Auto blowdown logic test as per SP 413B and auto actuation of APR subsystem as per SP 413C tests these relay coils	1.7×10^{-3}
932287-1Ø6A-3FC 932287-1Ø6A-5FC 932287-1Ø6A-7FC 932287-1Ø6A-9FC 932287-1Ø5A-1FC 932287-1Ø5A-3FC 932287-1Ø5A-5FC 932287-1Ø4A-1FC 932287-1Ø3A-9FC	Relay contacts fail to close	12000 hrs (detected during refueling outages)	Auto actuation of APR subsystem as per SP 413C (energizes APR valve solenoids)	1.8×10^{-3}
9Ø3287-3Ø2-1RC } A 903287-3Ø2-5RC } A 903287-3Ø2-9RC } B 903287-3Ø2-DRC } B 903287-3Ø2-FRD	Failure of reset switch or contact pair to remain	12000 hrs (detected during refueling outages)	Auto blowdown logic test as per SP 413B. Procedure SP 413C will also test "A" logic contact pairs yearly	1.8×10^{-4} 6.3×10^{-5}
9Ø3287-3Ø2-OER 9Ø3287-3Ø3-OER	Operator resets APR actuation logic during accident	No detection interval	Reset of timer will delay auto actuation by 120sec	3×10^{-3}
932287-1Ø8A-2RC 932287-1Ø8A-1RC 932287-1Ø8B-2RC 932287-1Ø8B-1RC	Failure of relay contacts to remain closed	One month	Tests on hi drywell pressure sensors and AC interlocks as per SP 412D and SP 413A respectively	3.6×10^{-5}

MILLSTONE 1
SYSTEM APR
SHEET #3

FAULT SUMMARY SHEETS

EVENT	DESCRIPTION	DETECTION INTERVAL	COMMENTS	UNAVAILABILITY
932287-1Ø8A-FRE 932287-1Ø8B-FRE	Failure of relay coil to remain energized	12000 hrs (detected during refueling outages)	Auto blowdown logic test as per SP 413B	$6x10^{-4}$
287-7Ø1A-FUS-LOF 287-7Ø2A-FUS-LOF 287-7Ø1B-FUS-LOF 287-7Ø2B-FUS-LOF	Failure of fuses on prime DC supply	Immediate	"Fuse monitor" annunciator on CRP 903	$2.4x10^{-5}$
932287-1Ø8A-4FC 932287-1Ø8A-3FC 932287-1Ø8B-4FC 932287-1Ø8B-3FC	Relay contacts fail to close	12000 hrs (detected during refueling outages)	Auto blowdown logic test as per SP 413B	$1.8x10^{-3}$
287-7Ø6A-FUS-LOF 287-7Ø5A-FUS-LOF 287-7Ø6B-FUS-LOF 287-7Ø5B-FUS-LOF	Failure of fuses on alternate D.C. supply	12000 hrs (detected during refueling outages)	Auto blowdown logic test as per SP 413B	$6x10^{-3}$
932287-112A-FTE 932153Ø-147-FTE 933153Ø-247-FTE 932143Ø-132A-FTE 933143Ø-132B-FTE 932287-112B-FTE	Relay coil fails to energize	One month	LPCI/LPCS pump interlock test as per SP 413A	$1x10^{-4}$
932153Ø-147-1FC 933153Ø-247-2FC 932143Ø-132A-1FC 933143Ø-132B-2FC	Relay contacts fail to close	One month	LPCI/LPCS pump interlock test as per SP 413A	$1x10^{-4}$

MILLSTONE 1
SYSTEM APR
SHEET #4

FAULT SUMMARY SHEETS

EVENT	DESCRIPTION	DETECTION INTERVAL	COMMENTS	UNAVAILABILITY
DC-11A2-23-FRC DC-11A2-20-FRC DC-11A1-25-FRC DC-11A1-26-FRC	Local faults on breaker	One month	LPCI/1LPCS pump interlock test as per SP 413A	3.6×10^{-4}
22Ø1A15Ø182A-XFC 2201A150182C-XFC 22Ø1B15Ø182B-XFC 2201B150182D-XFC LCLPS-1462D-XFC LCLPS-1462C-XFC	Contacts fail to close on pressure switch	One month	LPCI/LPCS pump interlock test as per SP 413A	1.4×10^{-4}
22Ø1A15Ø182A-TOM 22Ø1A15Ø182C-TOM 22Ø1B15Ø182B-TOM 22Ø1B15Ø182D-TOM LCLPS-1462C-TOM LCLPS-1462D-TOM	Pressure switch o.o.s. as a result of test or maintenance (i.e. not restored to service)	One month	LPCI/LPCS pump interlock test as per SP 413A	1×10^{-2}
22Ø1A15Ø182A-OMC 22Ø1A15Ø182C-OMC 22Ø1B15Ø182B-OMC 22Ø1B15Ø182D-OMC LCLPS-1462C-OMC LCLPS-1462D-OMC	Pressure switch miscalibrated	One month	LPCI/LPCS pump interlock test as per SP 413A	1×10^{-3}
LPCI-PUMP-A-OFF LPCI-PUMP-B-OFF LPCI-PUMP-C-OFF LPCI-PUMP-D-OFF	LPCI pump not running	N/A	Conditional events	
CS-PUMP-A-OFF CS-PUMP-B-OFF	Core spray pump not running	N/A	Conditional events	

MILLSTONE 1
SYSTEM APR
SHEET #5

FAULT SUMMARY SHEETS

EVENT	DESCRIPTION	DETECTION INTERVAL	COMMENTS	UNAVAILABILITY
932287-1Ø1A-FTE 932287-1Ø1B-FTE 932287-1Ø2A-FTE 932287-1Ø2B-FTE	Relay coil fails to energize	One month	Hi drywell pressure sensor test as per SP 412D	$1x10^{-4}$
932287-1Ø1A-1FC 932287-1Ø1A-3FC 932287-1Ø1B-1FC 932287-1Ø1B-3FC 932287-1Ø2A-1FC 932287-1Ø2A-3FC 932287-1Ø2B-1FC 932287-1Ø2B-3FC	Relay contacts fail to close	None (assume 10^5 hrs)	SP 412D only checks if relay energizes, not contacts closing; contacts never specifically tested	$3x10^{-2}$
9Ø3287-3Ø3-1RC 9Ø3287-3Ø3-5RC 9Ø3287-3Ø3-9RC 9Ø3287-3Ø3-DRC	Failure of reset switch contacts to remain closed	None (10^5 hrs assumed)	Part of seal-in circuit which is never tested separately	$3x10^{-3}$
9Ø3287-3Ø3-FRD	Reset switch fails to remain closed	None (10^5 hrs assumed)	Never specifically tested	$1x10^{-3}$
22Ø5PS-162ØA-XFC 22Ø6PS-162ØB-XFC 22Ø5PS-162ØC-XFC 22Ø6PS-162ØD-XFC	Failure of pressure switch contacts to close	One month	Hi drywell pressure sensor test as per SP 412D	$1.4x10^{-4}$

MILLSTONE 1
SYSTEM APR
SHEET #6

FAULT SUMMARY SHEETS

EVENT	DESCRIPTION	DETECTION INTERVAL	COMMENTS	UNAVAILABILITY
22Ø5PS-162ØA-TOM 22Ø6PS-162ØB-TOM 22Ø5PS-162ØC-TOM 22Ø6PS-162ØD-TOM	Pressure switch O.O.S. as a result of test or maint. (i.e. not restored to service)	One month	Sensor tested as per SP 412D	$1x10^{-2}$
22Ø5PS-162ØA-OMC 22Ø6PS-162ØB-OMC 22Ø5PS-162ØC-OMC 22Ø6PS-162ØD-OMC	Pressure switch miscalibrated	One month	Sensor tested as per SP 412D	$1x10^{-3}$
NO-HI-DRYWL-PRES NO-LO-RX-H2O-LVL	Drywell pressure < 2 PSIG Rx water level > 79" above TAF	N/A	Conditional events	
932143Ø-1Ø6A-FTE 932143Ø-1Ø6B-FTE 932143Ø-1Ø7A-FTE 932143Ø-1Ø7B-FTE	Relay coil fails	One month	Rx lo lo water level sensor test as per SP 412C	$1x10^{-4}$
932143Ø-1Ø6A-5FC 932143Ø-1Ø6B-5FC 932143Ø-1Ø7A-5FC 932143Ø-1Ø7B-5FC	Relay contacts fail to close	None (assume 10^5 hrs)	SP 412C only checks for relay coil energizing not contact pair closing, contact pair never specifically tested	$3x10^{-2}$

MILLSTONE 1
SYSTEM APR
SHEET #7

FAULT SUMMARY SHEETS

EVENT	DESCRIPTION	DETECTION INTERVAL	COMMENTS	UNAVAILABILITY
22Ø5263-72A2-XFC 22Ø6263-72B2-XFC 22Ø5263-72C2-XFC 22Ø6263-72D2-XFC	Water level switch contacts fail to close	One month	Rx lo lo water level sensor test as per SP 412C	1.4×10^{-4}
22Ø5263-72A2-TOM 22Ø6263-72B2-TOM 22Ø5263-72C2-TOM 22Ø6263-72D2-TOM	Water level sensor O.O.S. as result of test or maint. (i.e. not restored to service)	One month	Rx low water level sensor test as per SP 412C	1×10^{-2}
22Ø5263-72A2-OMC 22Ø6263-72B2-OMC 22Ø5263-72C2-OMC 22Ø6263-72D2-OMC	Water level sensor miscalibrated	One month	Sensor tested as per SP 412C	1×10^{-3}
932287-1Ø5B-FTE 932287-1Ø4B-FTE 932287-1Ø3B-FTE 932287-1Ø6B-FTE	Relay coil fails to energize	12000 hrs (tested during re-fueling outage)	Auto blowdown logic test as per SP 413B	1.7×10^{-3}
9321530-147-2FC 9331530-247-1FC 9321430-132A-2FC 9331430-132B-1FC	Relay contacts fail to close	One month	LPCI/LPCS pump inter-lock test as per SP 413A	1×10^{-4}
932287-11ØA-FTE 932287-11ØB-FTE 9321430/-131A-FTE 9331430/-131B-FTE 9321530/-145-FTE 9331530/-245-FTE	Relay coil fails to energize	One month	LPCI/LPCS pump interlock test as per SP 413A	1×10^{-4}

MILLSTONE 1
SYSTEM APR
SHEET #8

FAULT SUMMARY SHEETS

EVENT	DESCRIPTION	DETECTION INTERVAL	COMMENTS	UNAVAILABILITY
9321430-131A-1FC 9331430-131B-2FC 9321530-145-1FC 9331530-245-2FC	Relay contacts fail to close	One month	LPCI/LPCS pump interlock test as per SP 413A	$1.x10^{-4}$
2201APS1462A-XFC 2201BPS1462B-XFC 2201AP150172A-XFC 2201AP150172C-XFC 2201B150172B-XFC 2201B150172D-XFC	Pressure switch contacts fail to close	One month	LPCI/LPCS pump interlock test as per SP 413A	$1.4x10^{-4}$
2201APS1462A-TOM 2201APS1462B-TOM 2201A150172A-TOM 2201A150172C-TOM 2201B150172B-TOM 2201B150172D-TOM	Pressure switch O.O.S. due to test or maint. (i.e. not returned to service	One month	LPCI/LPCS pump interlock test as per SP 413A	$1x10^{-2}$
2201APS1462A-OMC 2201BPS1462A-OMC 2201A150172A-OMC 2201A150172C-OMC 2201B150172B-OMC 2201B150172D-OMC	Relay contacts fail to close	One month	LPCI/LPCS pump test as per SP 413A tests these contact pairs	$1x10^{-3}$

MILLSTONE 1
SYSTEM APR
SHEET #9

FAULT SUMMARY SHEETS

EVENT	DESCRIPTION	DETECTION INTERVAL	COMMENTS	UNAVAILABILITY
932287-1Ø3A-1FC 932287-112A-1FC 932287-1Ø5B-3FC 932287-1Ø4B-1FC 932287-1Ø3B-1FC 932287-112B-1FC 932287-1Ø6A-1FC 932287-11ØA-1FC 932287-1Ø6B-5FC 932287-1Ø6B-1FC 932287-11ØB-1FC 932287-1Ø6B-7FC 932287-1Ø5B-5FC	Relay contacts fail to close	None	SP 413A & SP 413B only check for coil energizing not contact pair closing-- Faults would be detected during system auto-actuation	$3x10^{-2}$
932287-1Ø5B-1FC 932287-1Ø6B-3FC	Relay contacts fail to close	None	Procedures SP 413A & 413B check for relay coil energizing not contact pair closing, faults would be detected during system auto-actuation	$3x10^{-2}$
933143Ø-1Ø6B-5FC 933143Ø-1Ø7B-5FC	Relay contacts fail to close	None (assume 10^5 hrs)	SP 412C only checks relay coil not contact pairs	$3x10^{-2}$
933143Ø-1Ø6B-FTE 933143Ø-1Ø7B-FTE	Relay coil fails to energize	One month	Tested during the performance of SP 412C	$1x10^{-4}$

MILLSTONE 1
SYSTEM APR
SHEET #10

FAULT SUMMARY SHEETS

EVENT	DESCRIPTION	DETECTION INTERVAL	COMMENTS	UNAVAILABILITY
932287-1Ø3B-9FC 932287-1Ø6B-9FC	Relay contacts fail to close	None (assume 10^5 hrs)	Only relay coil tested not contact pair	$3x10^{-2}$

MILLSTONE 1
SYSTEM APR
SHEET #11

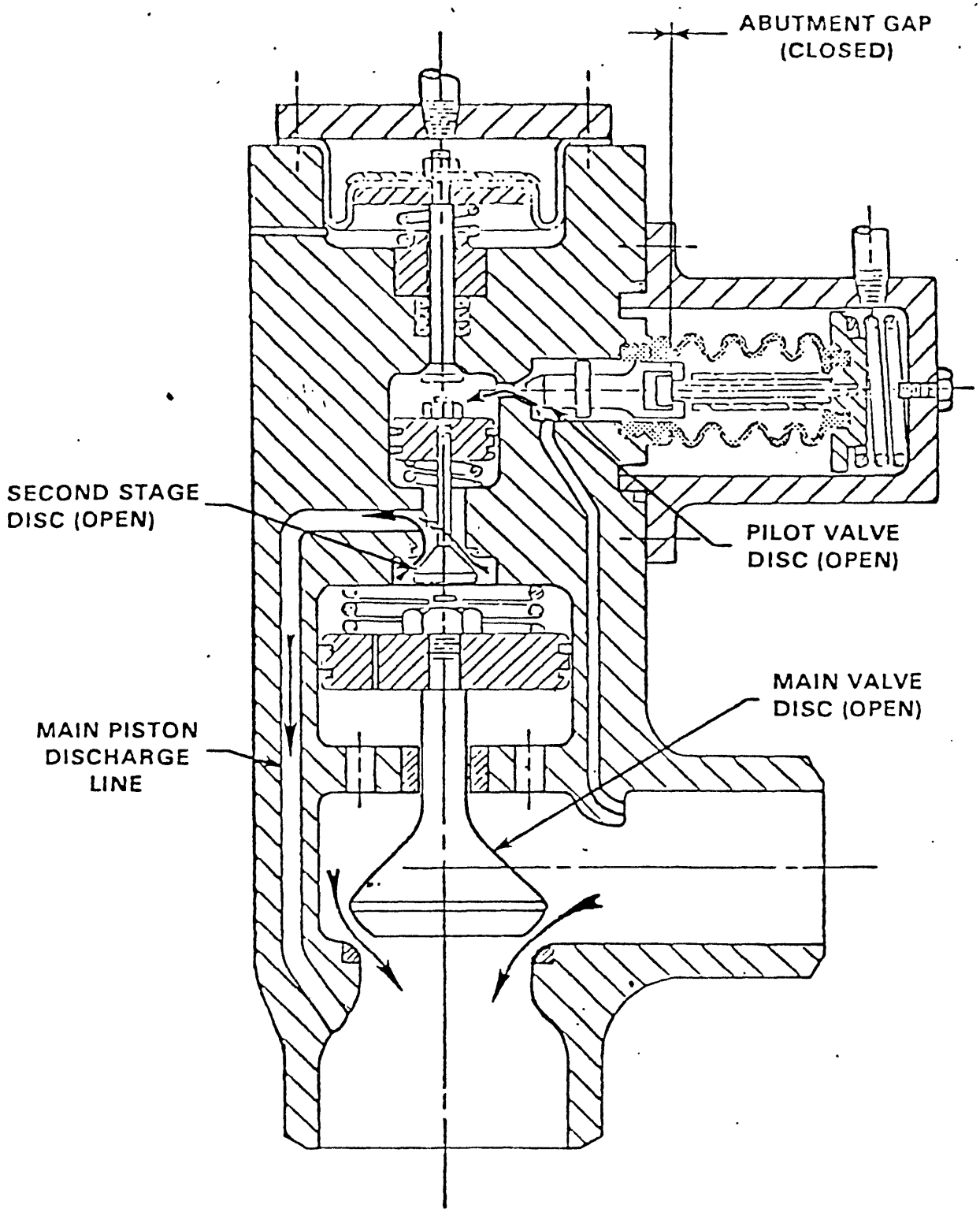


FIGURE C1 **VALVE SCHEMATIC (OPEN)**
SAFETY/RELIEF VALVE OPERATION

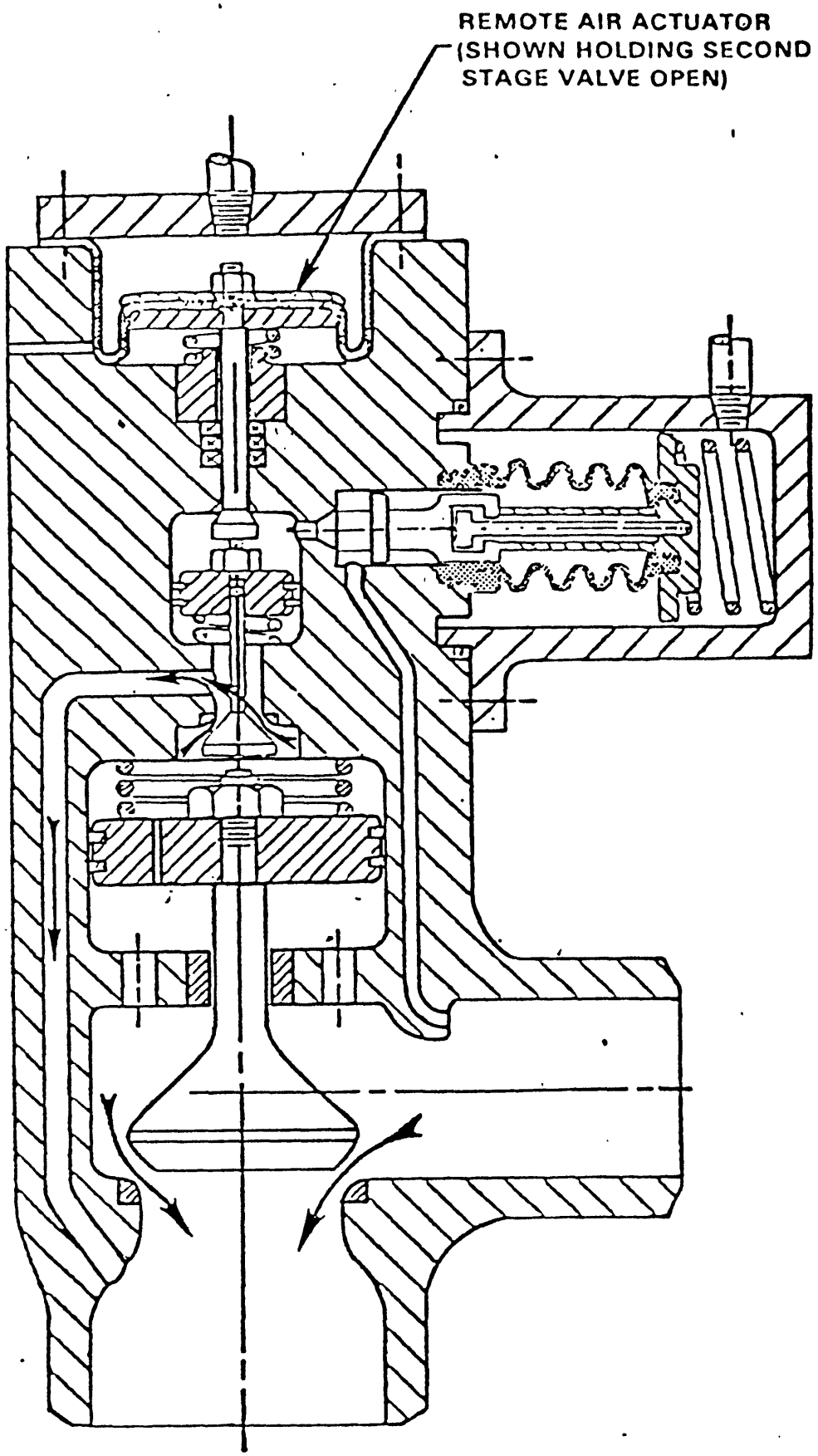


FIGURE C2 VALVE SCHEMATIC REMOTE ACTUATION

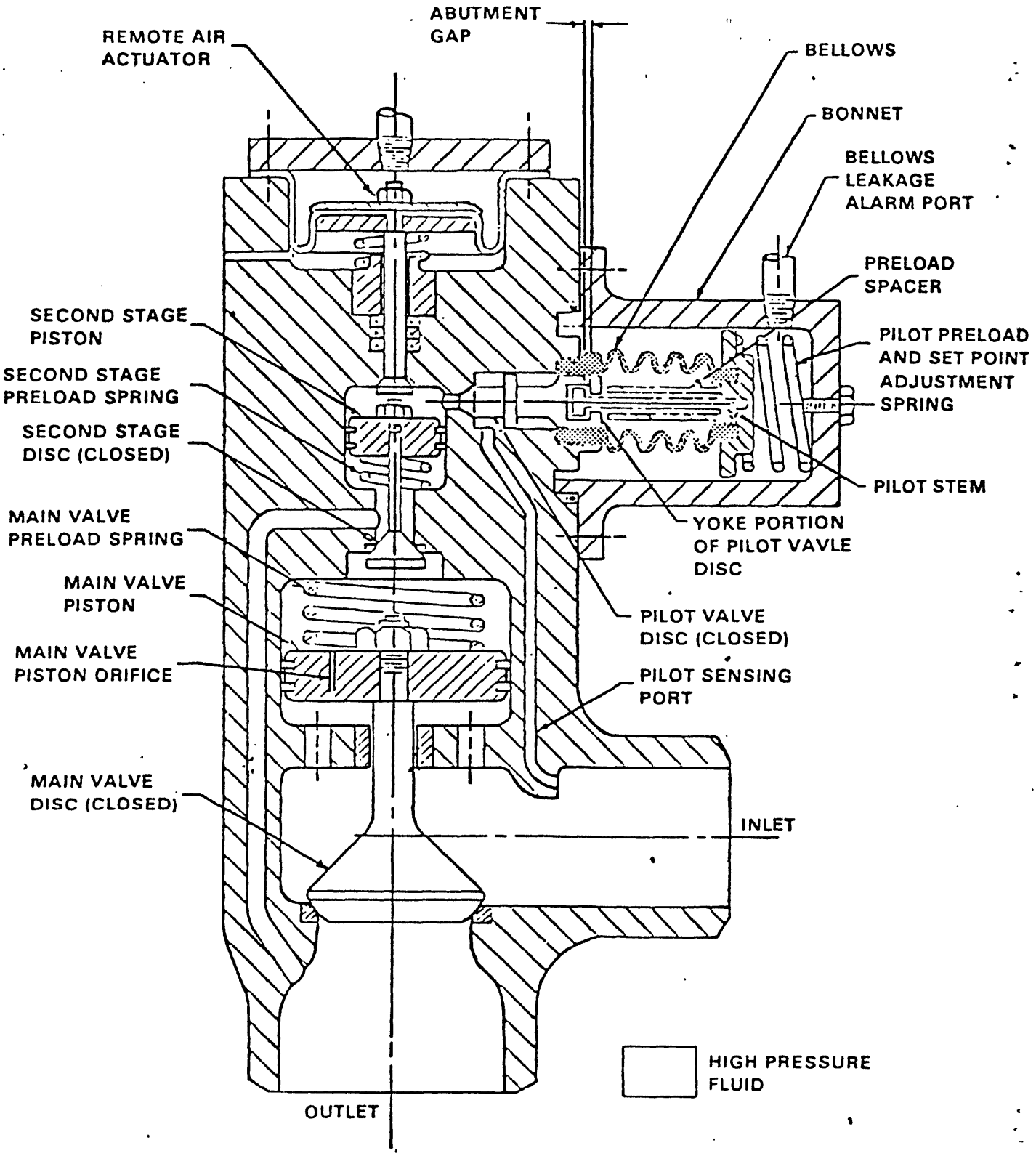


Figure C.3 **VALVE SCHEMATIC (CLOSED)**

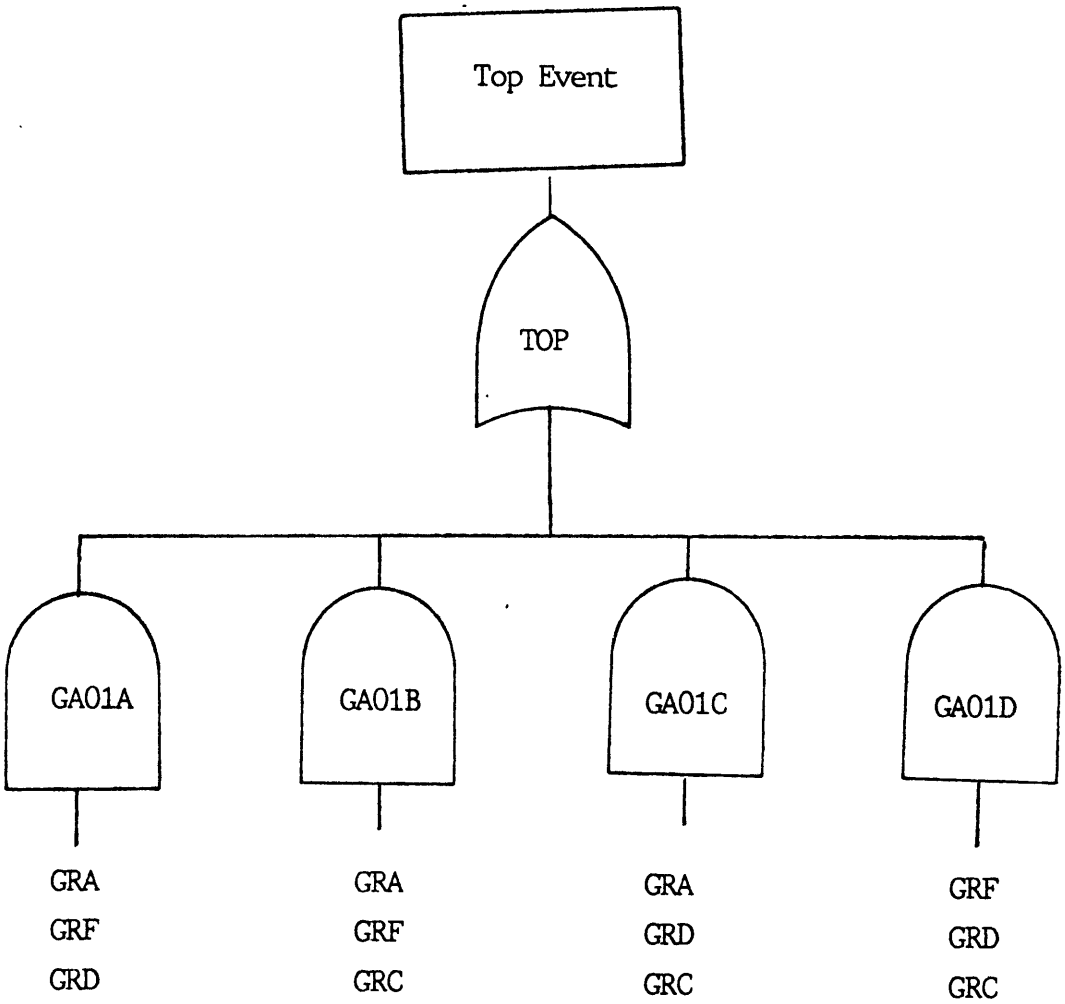
Front Line System		Support System		Failure Mode	Failure Effect
System	Components	System	Components		
APR	Air operated valve	Instrument	Air Operator	Loss of air	Emergency air accumulators
	MS-3A	Air			act as back-up air supply;
	MS-3C				complete loss of air supply
	MS-3D				causes valve to fail as is
	MS-3F				(N. C.)
APR	Air valve solenoid				
	MS-3A	125V	Bus 11A-2	Low or zero	Auto bus transfer to DC Bus
	MS-3C	DC Power		voltage	11A-1 valve fails as is (NC)
	MS-3D				if bus transfer fails
	MS-3F				

Table C.1 APR System Interfaces Failure Modes and Effects

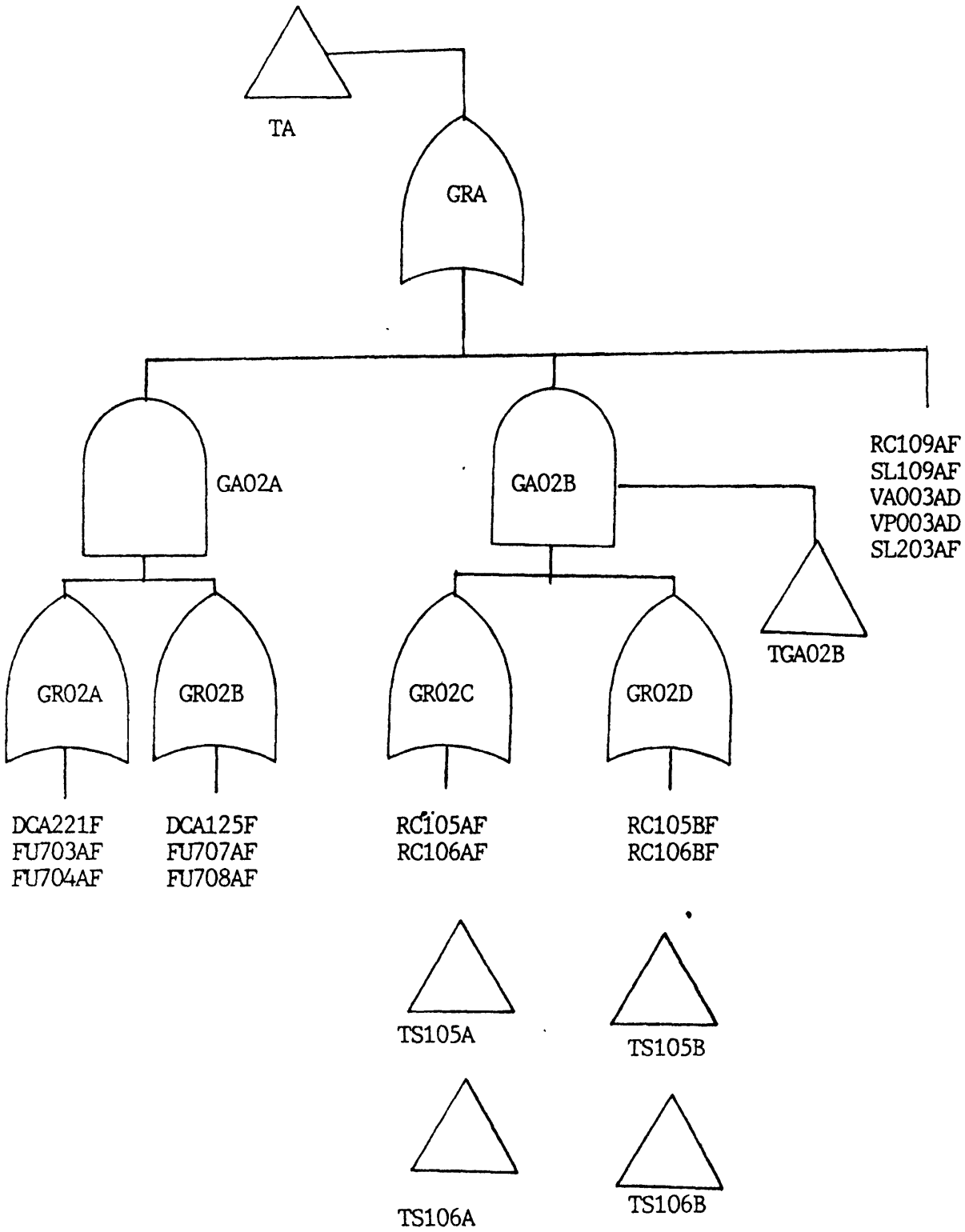
Sensors	Function	Setpoint
2205/1620A 2206/1620B 2205/1620C 2260/1260D	High drywell pressure indication	2 psig
2205/263-72A 2206/263-72B 2205/263-72C 2206/263-72D	Reactor low-low water indication	79" above the top of active fuel
Local/1462C 2201A/1462A 2201B/1462B Local/1462D	Core spray pumps discharge pressure switch	100 psig
2201A/1501-82A 2201B/1501-82B 2201C/1501-82C 2201D/1501-82D	LPCI pumps discharge pressure switch	100 psig

Table C.2: APR Instrumentation

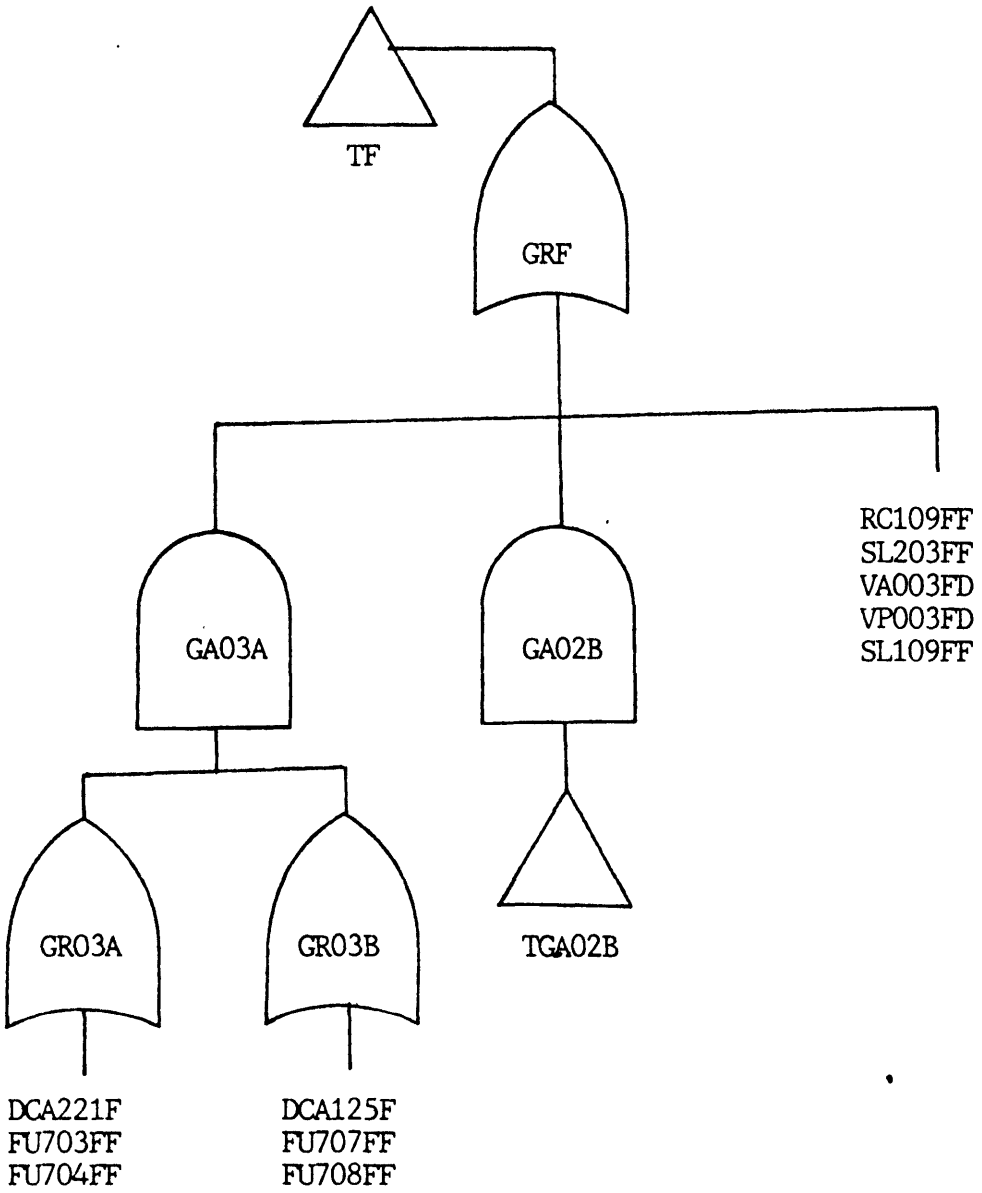
APPENDIX D: ADP (Automatic Remote Actuation Mode) Fault Tree with TOP EVENT - Less Than Two APR Valves Operate to Blowdown the Reactor Vessel on Demand. (25 Sheets)



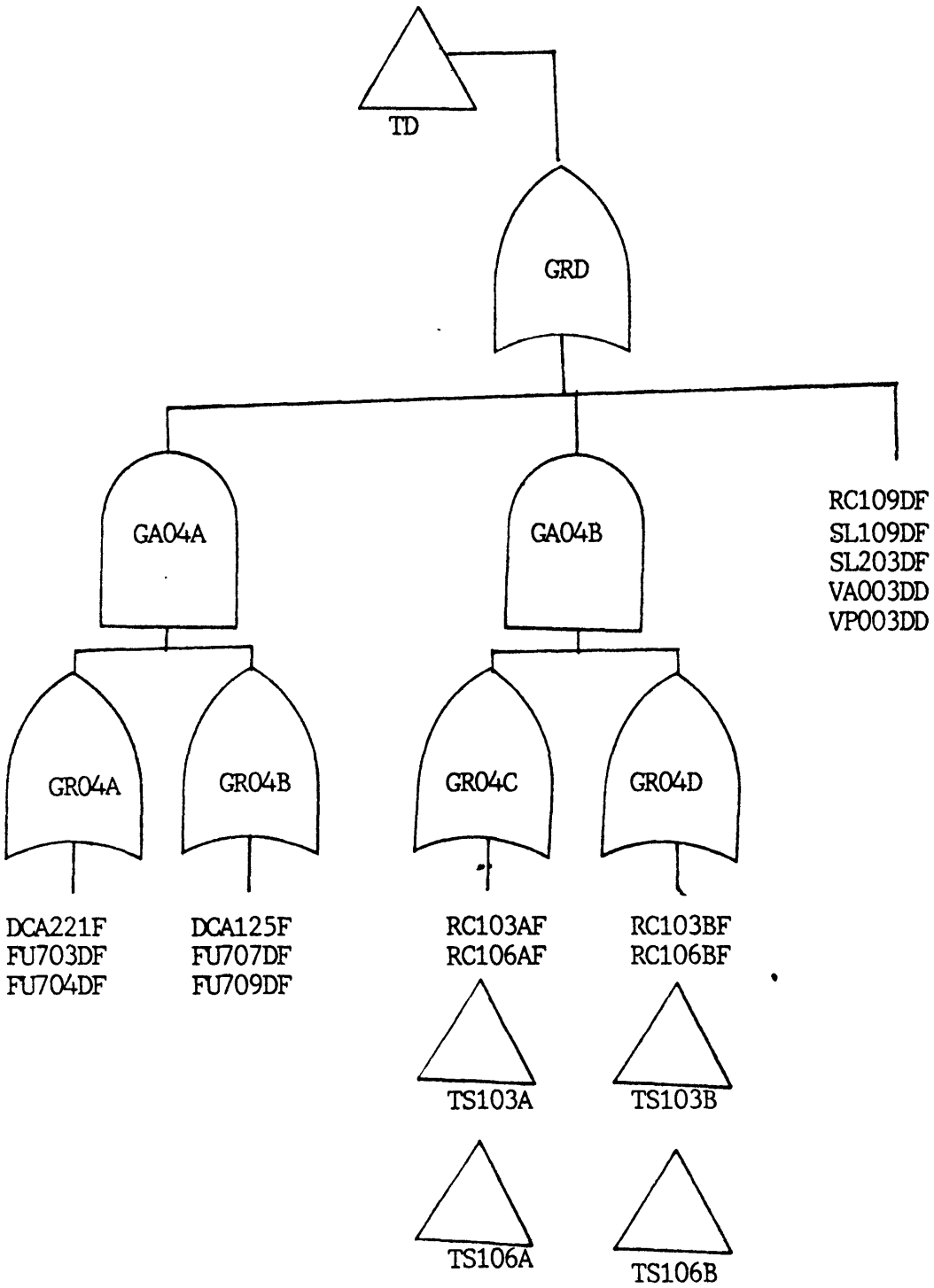
ADP Fault Tree (Sheet 1 of 25)



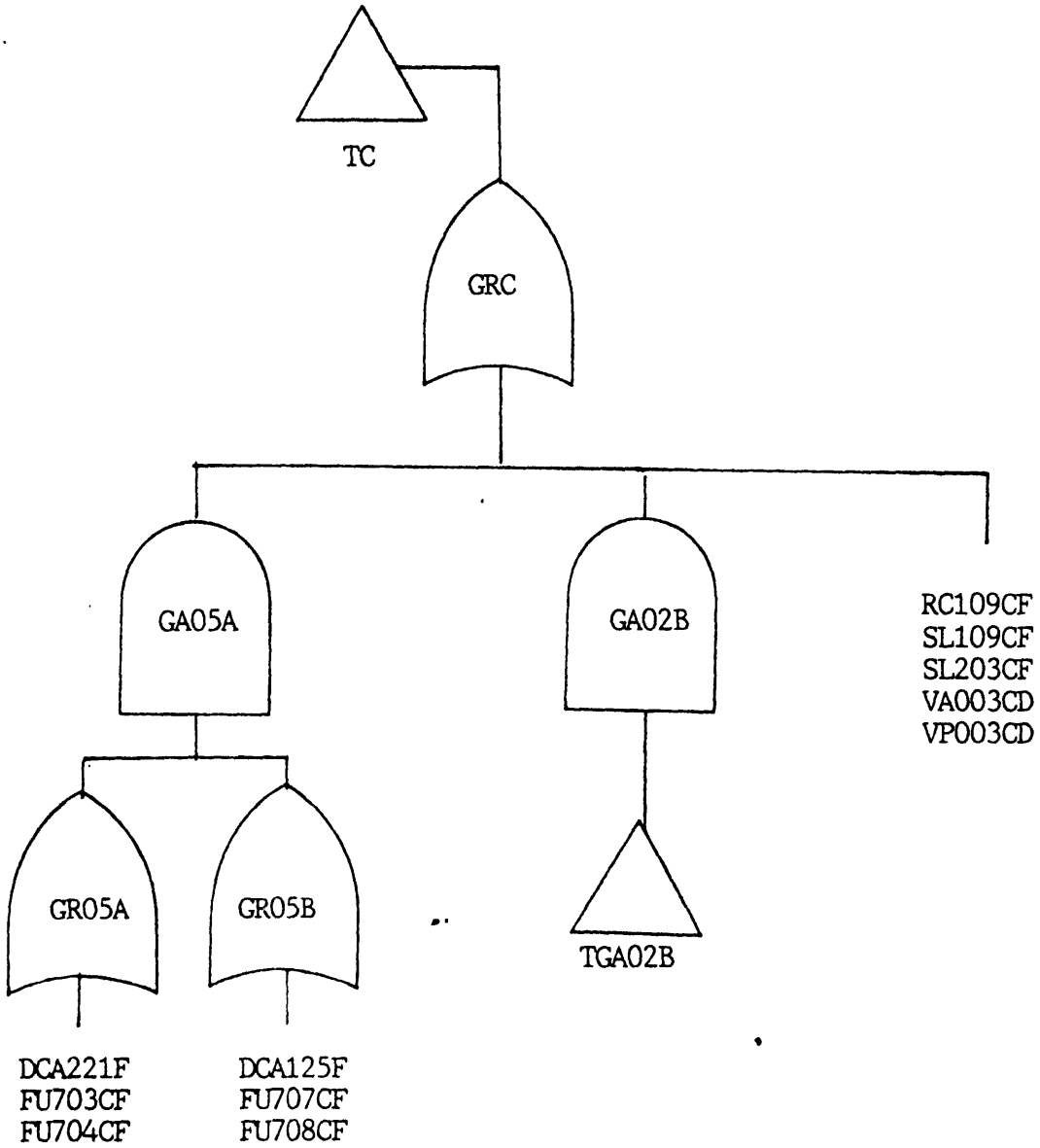
ADP Fault Tree (Sheet 2 of 25)



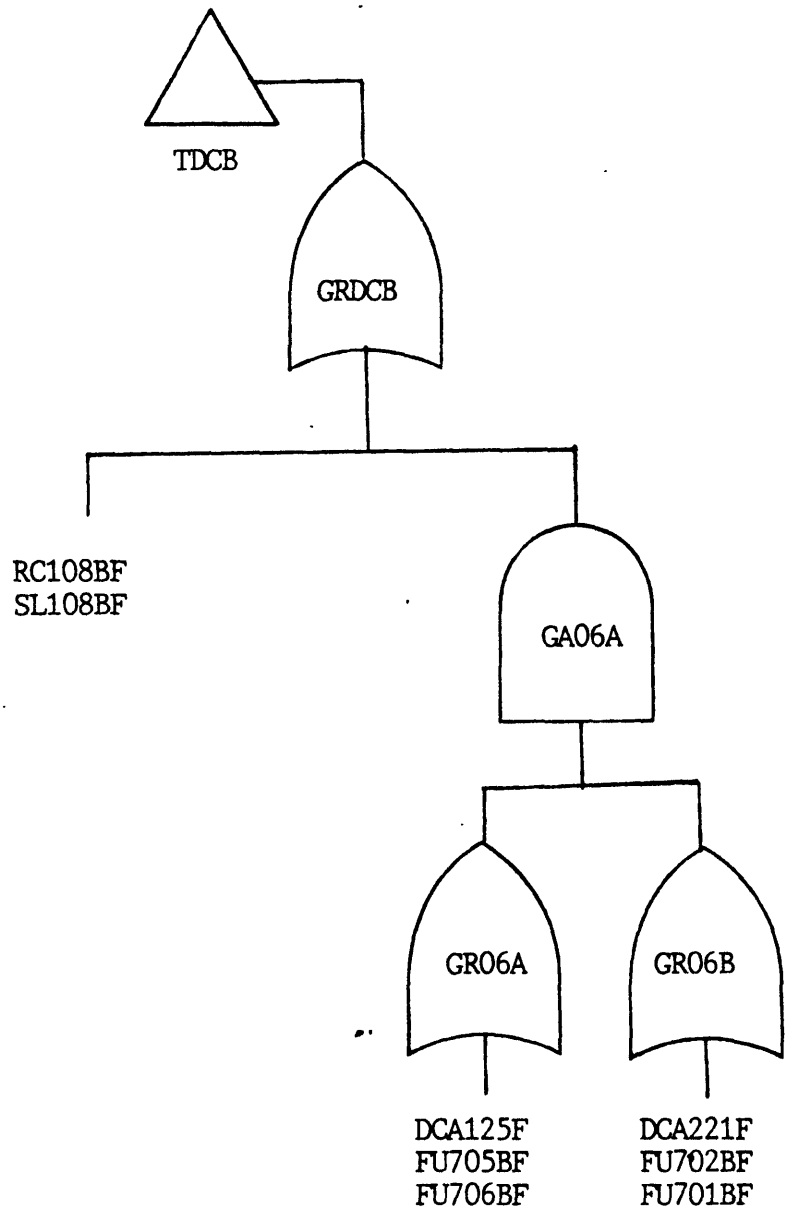
ADP Fault Tree (Sheet 3 of 25)



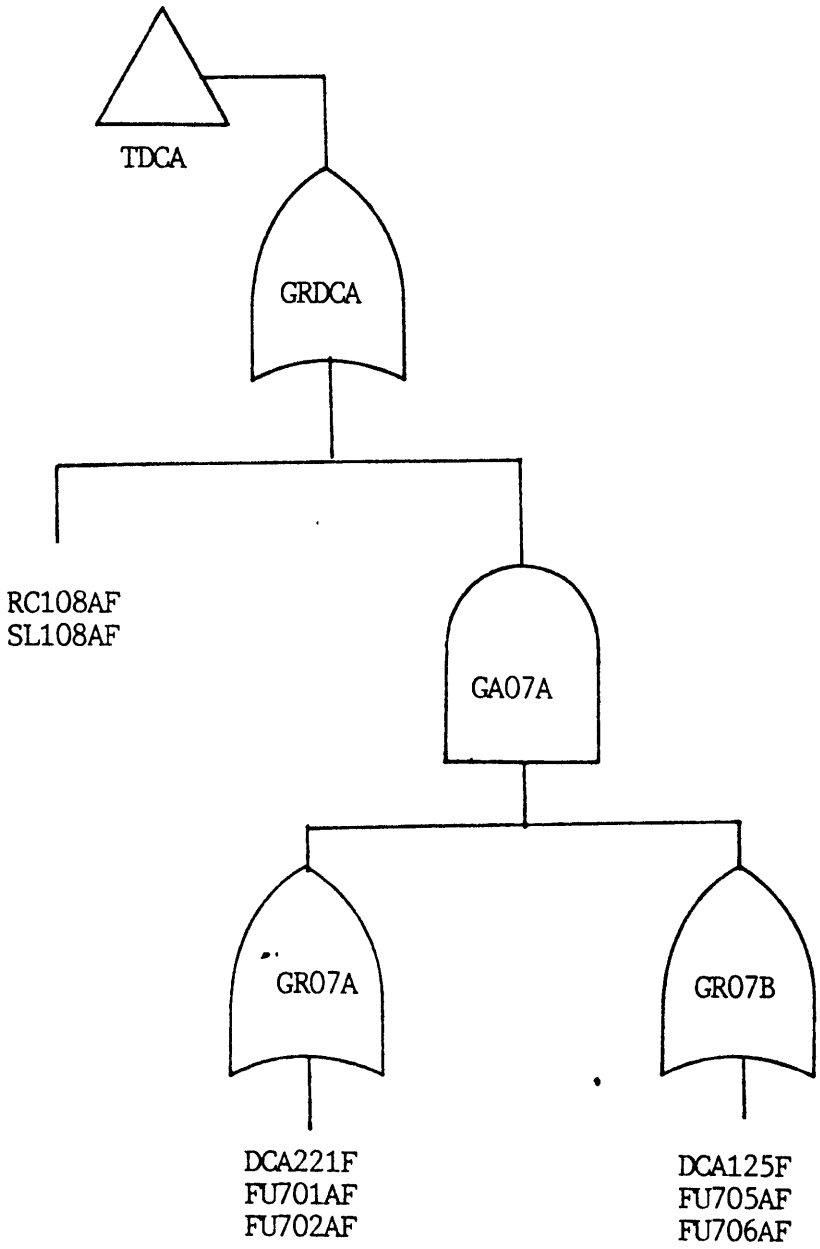
ADP Fault Tree (Sheet 4 of 25)



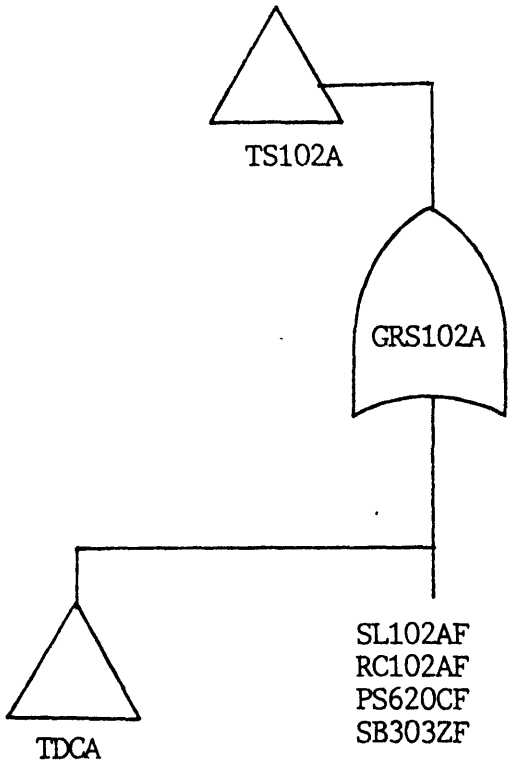
ADP Fault Tree (Sheet 5 of 25)



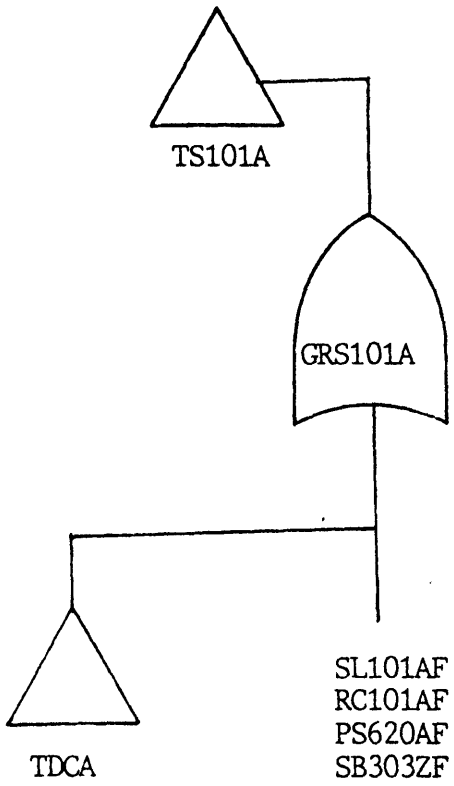
ADP Fault Tree (Sheet 6 of 25)



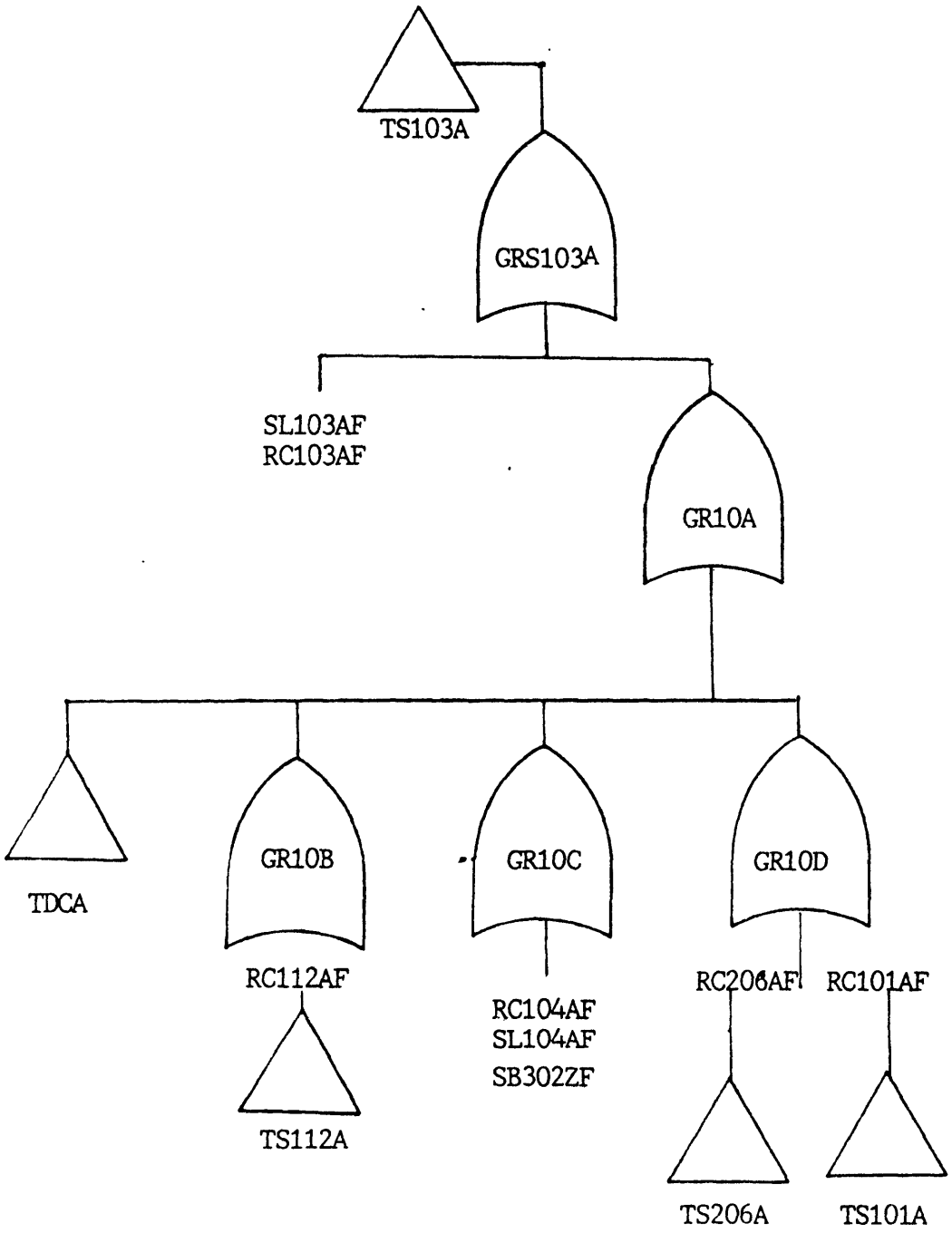
ADP Fault Tree (Sheet 7 of 25)



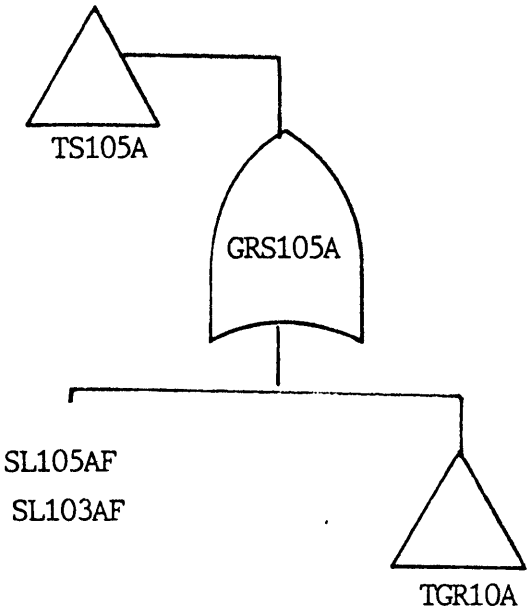
ADP Fault Tree (Sheet 8 of 25)



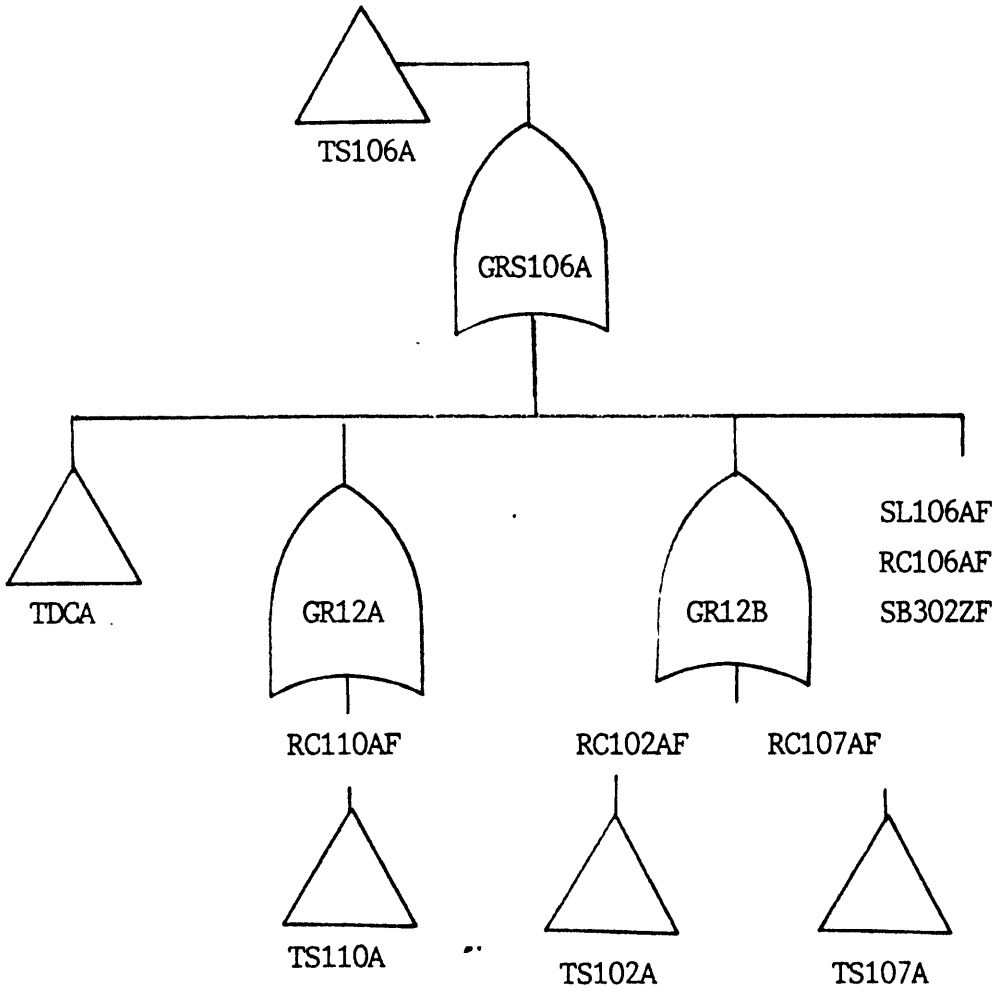
ADP Fault Tree (Sheet 9 of 25)



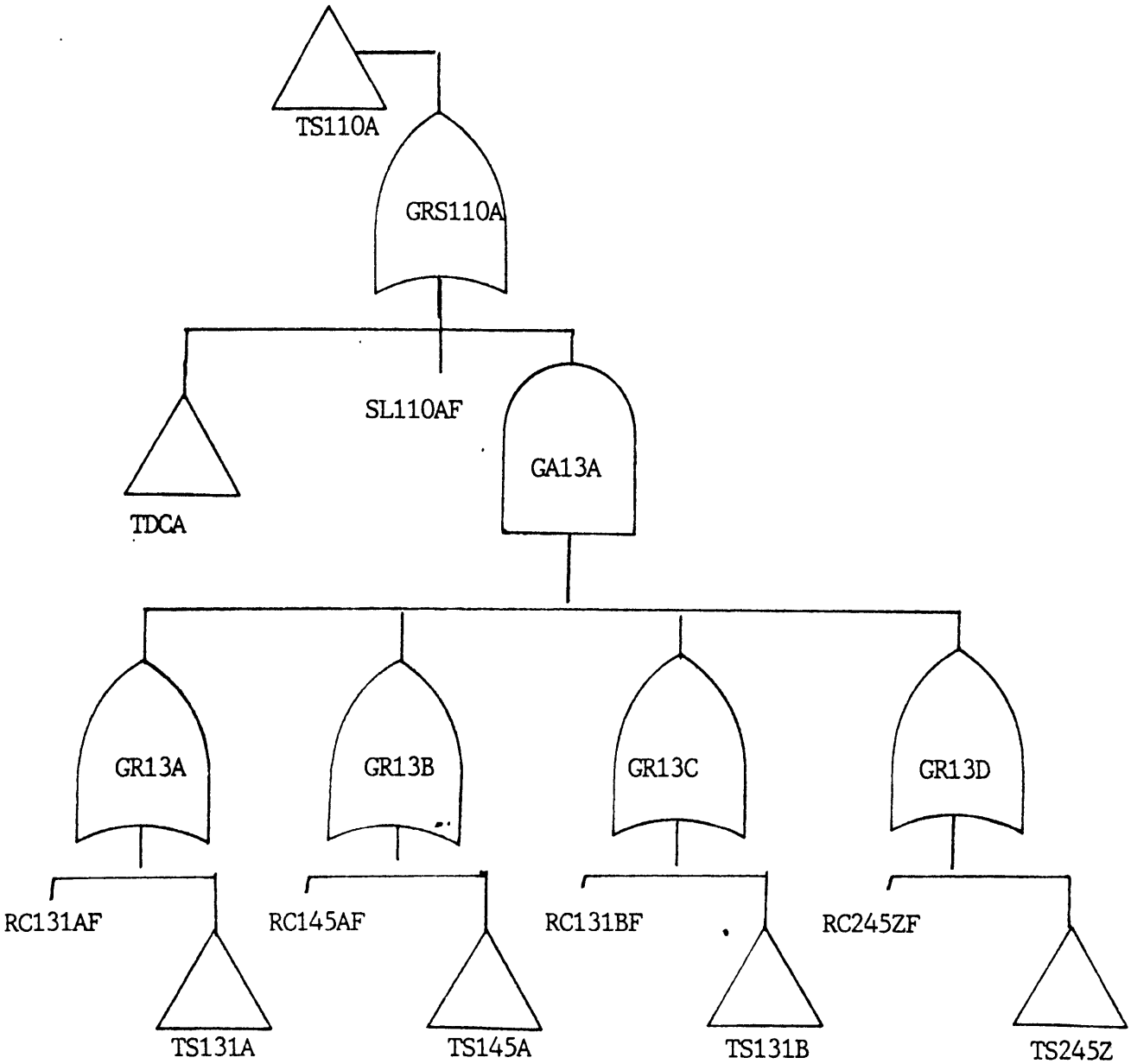
ADP Fault Tree (Sheet 10 of 25)



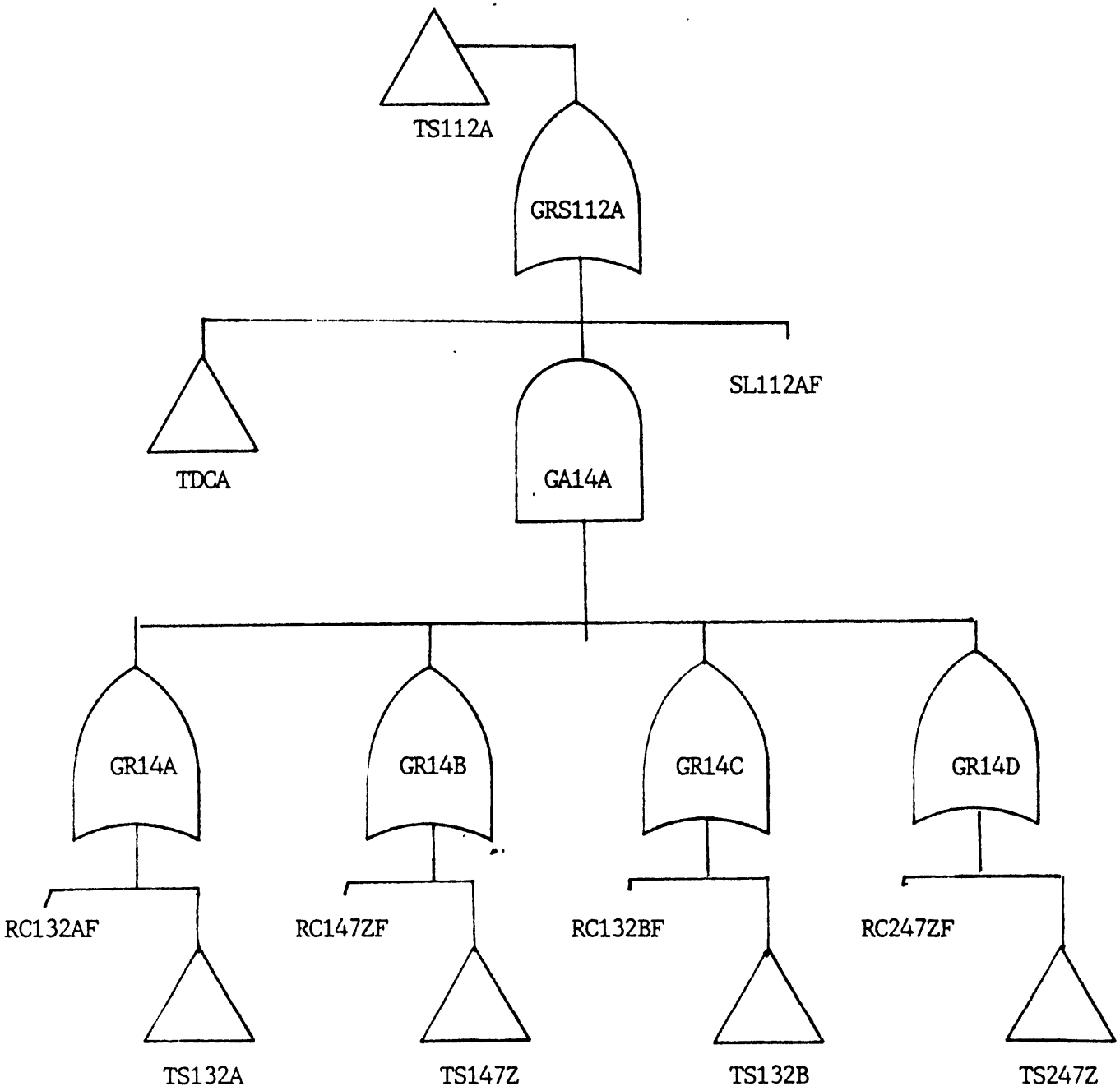
ADP Fault Tree (Sheet 11 of 25)



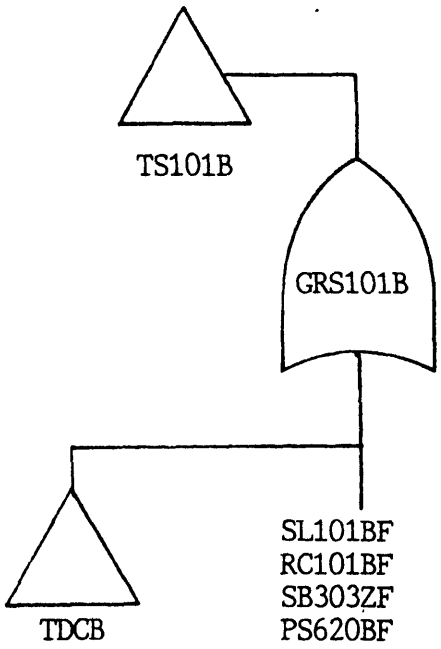
ADP Fault Tree (Sheet 12 of 25)

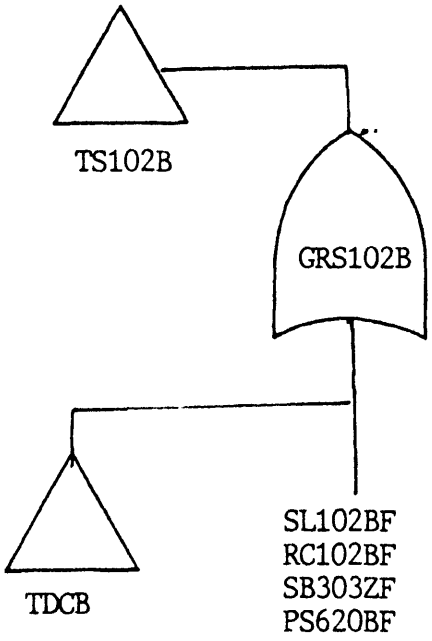


ADP Fault Tree (Sheet 13 of 25)

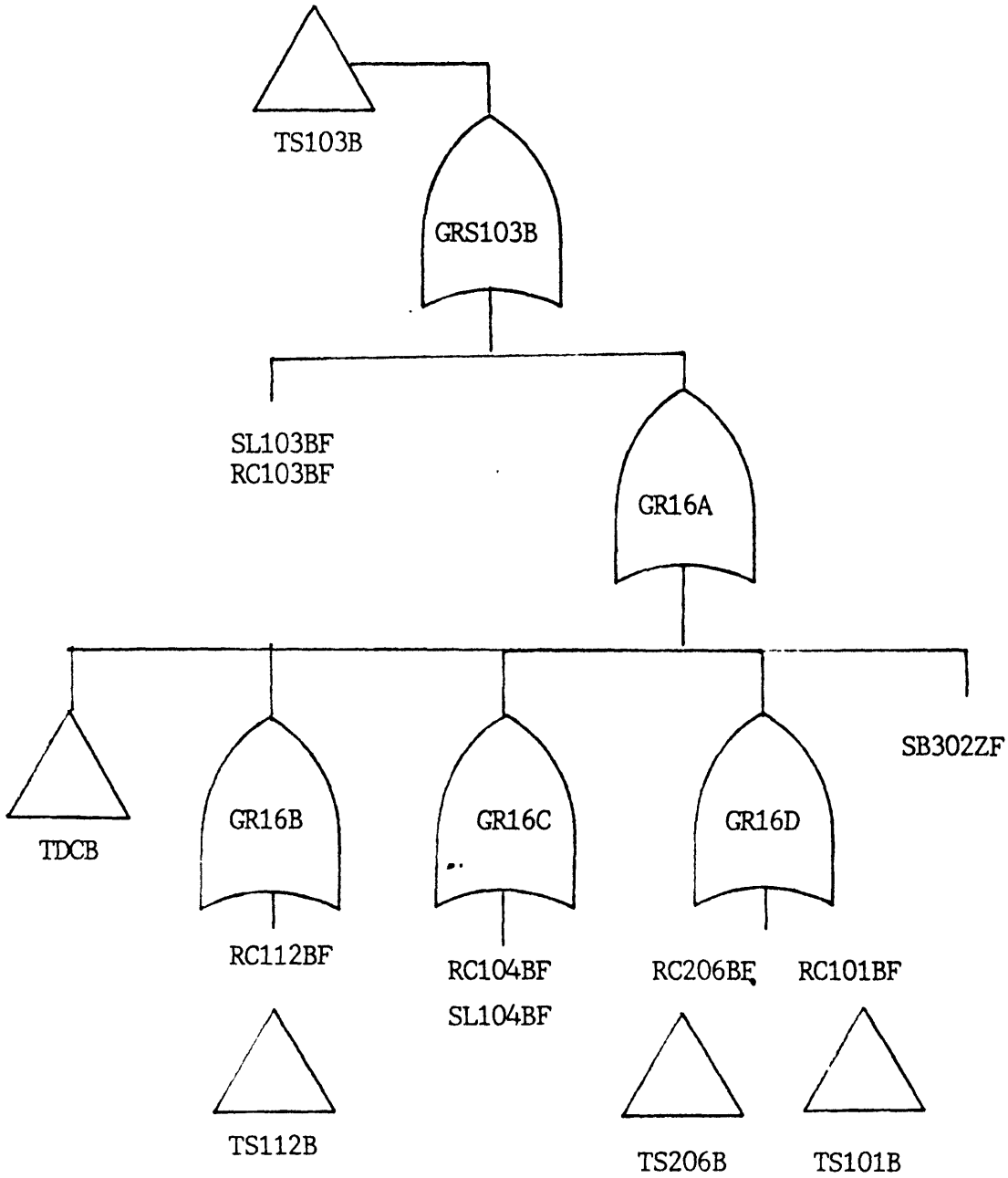


ADP Fault Tree (Sheet 14 of 25)

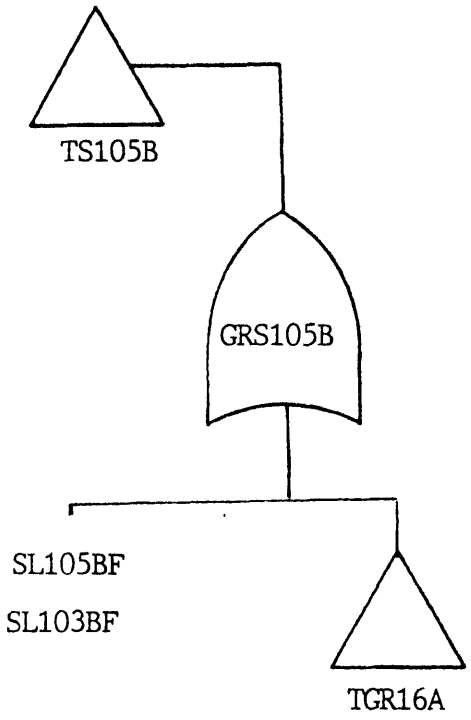




ADP Fault Tree (Sheet 15 of 25)



ADP Fault Tree (Sheet 16 of 25)



ADP FAult Tree (Sheet 17 of 25)

APPENDIX E: Output of DPD Code for External Common Initiating Events Analysis (Sample Problem)

INPUT DATA TO HADES

```
----+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*DATA SET ONE: COMMON INITIATORS DATA
    1
SEISMICITY                        SE    9
  .75000E-01   FTO1  -.76000        -2.6632          .0
  .15000       FTO1  -.97500        -2.0538          .0
  .75000E-01   FTO1  -1.1000        -1.8364          .0
  .50000E-01   FTO1  -.77780        -2.7350          .0
  .10000       FTO1  -.86250        -2.4913          .0
  .50000E-01   FTO1  -.93330        -2.3268          .0
  .12500       FTO1  -.93750        -2.3427          .0
  .25000       FTO1  -1.1000        -1.9727          .0
  .12500       FTO1  -1.1750        -1.8404          .0
*END

----+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*DATA SET TWO: COMPONENT DATA
    5
WATER STORAGE TANK                TK
SE       5
  .20000       FTO2   .57260        .28000          .0
  .20000       FTO2   .71380        .28000          .0
  .20000       FTO2   .83000        .28000          .0
  .20000       FTO2   .96510        .28000          .0
  .20000       FTO2   1.2031        .28000          .0
*END
PUMPING TRAIN                     PT
SE       5
  .20000       FTO2   .39740        .15000          .0
  .20000       FTO2   .52240        .15000          .0
  .20000       FTO2   .63000        .15000          .0
  .20000       FTO2   .75970        .15000          .0
  .20000       FTO2   .99880        .15000          .0
*END
BUILDING STRUCTURE                ST
SE       5
  .20000       FTO2   .51010        .30000          .0
  .20000       FTO2   .63110        .30000          .0
```

```
----+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
  .20000       FTO2    .73000         .30000         .0
  .20000       FTO2    .84440         .30000         .0
  .20000       FTO2    1.0447         .30000         .0
*END
DIESEL GENERATOR                DG
SE       5
  .20000       FTO2    .53560         .35000         .0
  .20000       FTO2    .70950         .35000         .0
  .20000       FTO2    .86000         .35000         .0
  .20000       FTO2    1.0425         .35000         .0
  .20000       FTO2    1.3810         .35000         .0
*END
OFF-SITE POWER                  OP
SE       5
  .20000       FTO2    .14520         .20000         .0
  .20000       FTO2    .17560         .20000         .0
  .20000       FTO2    .20000         .20000         .0
  .20000       FTO2    .22780         .20000         .0
  .20000       FTO2    .27540         .20000         .0
*END

----+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*DATA SET THREE: MINIMAL CUT SET DATA
    4
    1     ST
    2     PTA  PTB
    2     DG   OP
    2     TK   PTB
*END

------------------------ END OF INPUT CARD IMAGES ------------------------
```

INPUT SUMMARY

NUMBER OF EXTERNAL COMMON INITIATORS (NCI) ----- 1

NUMBER OF COMPONENTS (NCP) ---------- 5

NUMBER OF CUT SETS (NCS) ---------- 4

COMMON INITIATING EVENTS	ABBREVIATIONS
SEISMICITY	SE

COMPONENTS' NAMES	ABBREVIATIONS
WATER STORAGE TANK	TK
PUMPING TRAIN	PT
BUILDING STRUCTURE	ST
DIESEL GENERATOR	DG
OFF-SITE POWER	OP

OUTPUT FROM HADES

COMPONENT FAILURE FREQUENCY DISTRIBUTION

COMPONENT: WATER STORAGE TANK (TK)
CAUSE: SEISMICITY (SE)
NUMBER OF DOUBLETS: 45

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
2.5000E-02	2.5000E-02	6.7300E-10
5.0000E-02	7.5000E-02	1.1106E-09
2.5000E-02	.10000	2.7225E-09
1.0000E-02	.11000	4.0234E-09
2.5000E-02	.13500	6.5834E-09
2.0000E-02	.15500	9.2552E-09
1.5000E-02	.17000	9.7572E-09
5.0000E-02	.22000	1.0141E-08
1.0000E-02	.23000	2.1617E-08
2.5000E-02	.25500	2.2068E-08
2.5000E-02	.28000	2.4744E-08
3.0000E-02	.31000	2.8601E-08
1.0000E-02	.32000	3.2157E-08
5.0000E-02	.37000	3.6414E-08
2.0000E-02	.39000	7.0157E-08
2.5000E-02	.41500	7.2856E-08
2.5000E-02	.44000	7.9236E-08
1.5000E-02	.45500	8.1363E-08
1.5000E-02	.47000	8.1524E-08
1.0000E-02	.48000	1.0505E-07
5.0000E-02	.53000	1.1142E-07
1.0000E-02	.54000	1.5594E-07
2.5000E-02	.56500	2.0429E-07
3.0000E-02	.59500	2.1913E-07
2.0000E-02	.61500	2.2019E-07
1.5000E-02	.63000	2.7488E-07
1.0000E-02	.64000	2.9123E-07
2.5000E-02	.66500	3.3813E-07
5.0000E-02	.71500	4.4579E-07

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
1.0000E-02	.72500	4.7081E-07
1.5000E-02	.74000	5.6880E-07
2.0000E-02	.76000	5.8419E-07
3.0000E-02	.79000	6.9301E-07
2.5000E-02	.81500	7.1863E-07
1.5000E-02	.83000	7.8743E-07
1.0000E-02	.84000	1.0064E-06
1.0000E-02	.85000	1.1959E-06
1.5000E-02	.86500	1.6744E-06
3.0000E-02	.89500	1.8532E-06
2.0000E-02	.91500	1.8850E-06
1.5000E-02	.93000	2.8542E-06
1.0000E-02	.94000	3.5977E-06
1.5000E-02	.95500	4.1311E-06
3.0000E-02	.98500	6.0458E-06
1.5000E-02	1.0000	1.1838E-05

OUTPUT FROM HADES

COMPONENT FAILURE FREQUENCY DISTRIBUTION

COMPONENT: PUMPING TRAIN (PT)
CAUSE: SEISMICITY (SE)
NUMBER OF DOUBLETS: 45

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
2.5000E-02	2.5000E-02	3.8843E-11
5.0000E-02	7.5000E-02	7.5022E-11
2.5000E-02	.10000	2.3924E-10
1.0000E-02	.11000	3.6417E-10
1.5000E-02	.12500	7.9698E-10
2.0000E-02	.14500	9.3801E-10
1.0000E-02	.15500	2.4345E-09
3.0000E-02	.18500	2.8231E-09
2.5000E-02	.21000	4.5490E-09
5.0000E-02	.26000	7.9734E-09
1.5000E-02	.27500	9.7861E-09
2.5000E-02	.30000	2.1618E-08
1.0000E-02	.31000	3.2314E-08
2.5000E-02	.33500	4.0574E-08
5.0000E-02	.38500	6.4983E-08
1.5000E-02	.40000	7.5438E-08
2.0000E-02	.42000	7.7591E-08
2.5000E-02	.44500	1.4993E-07
1.0000E-02	.45500	1.8848E-07
2.5000E-02	.48000	2.1334E-07
1.0000E-02	.49000	2.1984E-07
3.0000E-02	.52000	2.3757E-07
5.0000E-02	.57000	3.1005E-07
2.0000E-02	.59000	4.8977E-07
1.5000E-02	.60500	5.4711E-07
2.5000E-02	.63000	5.9498E-07
1.5000E-02	.64500	7.2683E-07
1.0000E-02	.65500	8.5207E-07
1.0000E-02	.66500	1.1065E-06

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
2.5000E-02	.69000	1.2974E-06
3.0000E-02	.72000	1.5251E-06
5.0000E-02	.77000	1.6699E-06
2.0000E-02	.79000	1.7313E-06
1.5000E-02	.80500	2.2785E-06
2.5000E-02	.83000	2.5208E-06
1.0000E-02	.84000	3.4924E-06
1.0000E-02	.85000	3.5667E-06
1.5000E-02	.86500	4.0708E-06
3.0000E-02	.89500	5.4907E-06
2.0000E-02	.91500	6.2409E-06
1.5000E-02	.93000	1.0203E-05
1.0000E-02	.94000	1.1259E-05
1.5000E-02	.95500	1.2332E-05
3.0000E-02	.98500	2.0192E-05
1.5000E-02	1.0000	3.5437E-05

OUTPUT FROM HADES

COMPONENT FAILURE FREQUENCY DISTRIBUTION

COMPONENT: BUILDING STRUCTURE (ST)
CAUSE: SEISMICITY (SE)
NUMBER OF DOUBLETS: 45

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
2.5000E-02	2.5000E-02	4.9398E-09
5.0000E-02	7.5000E-02	7.5653E-09
2.5000E-02	.10000	1.6301E-08
1.0000E-02	.11000	2.3725E-08
2.5000E-02	.13500	3.0005E-08
5.0000E-02	.18500	4.3241E-08
2.0000E-02	.20500	5.1542E-08
1.5000E-02	.22000	6.0360E-08
2.5000E-02	.24500	8.3278E-08
2.5000E-02	.27000	8.7234E-08
1.0000E-02	.28000	1.1413E-07
1.0000E-02	.29000	1.1950E-07
5.0000E-02	.34000	1.2069E-07
3.0000E-02	.37000	1.6111E-07
2.5000E-02	.39500	2.1478E-07
2.5000E-02	.42000	2.2520E-07
2.0000E-02	.44000	2.4601E-07
5.0000E-02	.49000	2.9944E-07
1.0000E-02	.50000	3.0500E-07
1.5000E-02	.51500	3.1704E-07
1.5000E-02	.53000	4.1532E-07
2.5000E-02	.55500	4.9218E-07
1.0000E-02	.56500	5.1710E-07
2.0000E-02	.58500	6.0310E-07
1.0000E-02	.59500	6.9130E-07
2.5000E-02	.62000	7.4489E-07
3.0000E-02	.65000	7.7671E-07
1.5000E-02	.66500	8.3337E-07
5.0000E-02	.71500	9.3755E-07

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
1.0000E-02	.72500	1.2178E-06
2.0000E-02	.74500	1.3104E-06
2.5000E-02	.77000	1.3769E-06
1.5000E-02	.78500	1.8187E-06
1.0000E-02	.79500	1.9029E-06
3.0000E-02	.82500	1.9174E-06
1.5000E-02	.84000	1.9451E-06
1.0000E-02	.85000	2.5343E-06
2.0000E-02	.87000	3.3876E-06
1.5000E-02	.88500	4.1690E-06
3.0000E-02	.91500	4.1941E-06
1.5000E-02	.93000	5.5764E-06
1.0000E-02	.94000	6.1351E-06
1.5000E-02	.95500	8.4204E-06
3.0000E-02	.98500	1.0938E-05
1.5000E-02	1.0000	1.9448E-05

OUTPUT FROM HADES

COMPONENT FAILURE FREQUENCY DISTRIBUTION

COMPONENT: DIESEL GENERATOR (DG)
CAUSE: SEISMICITY (SE)
NUMBER OF DOUBLETS: 45

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
2.5000E-02	2.5000E-02	1.2845E-09
5.0000E-02	7.5000E-02	1.9830E-09
2.5000E-02	.10000	4.3281E-09
1.0000E-02	.11000	6.3089E-09
2.0000E-02	.13000	1.3781E-08
2.5000E-02	.15500	1.4036E-08
1.5000E-02	.17000	1.5979E-08
5.0000E-02	.22000	2.0098E-08
1.0000E-02	.23000	3.0672E-08
2.5000E-02	.25500	3.8337E-08
3.0000E-02	.28500	4.3034E-08
1.0000E-02	.29500	5.4957E-08
2.5000E-02	.32000	5.5680E-08
5.0000E-02	.37000	7.6117E-08
1.5000E-02	.38500	1.1198E-07
2.0000E-02	.40500	1.1278E-07
2.5000E-02	.43000	1.3282E-07
1.5000E-02	.44500	1.4619E-07
2.5000E-02	.47000	1.8526E-07
1.0000E-02	.48000	1.8816E-07
1.0000E-02	.49000	2.3657E-07
5.0000E-02	.54000	2.4227E-07
3.0000E-02	.57000	3.5615E-07
2.0000E-02	.59000	3.6916E-07
2.5000E-02	.61500	3.8680E-07
1.5000E-02	.63000	5.1717E-07
1.0000E-02	.64000	5.4127E-07
1.0000E-02	.65000	7.4065E-07
2.5000E-02	.67500	8.1395E-07

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
1.5000E-02	.69000	8.3137E-07
5.0000E-02	.74000	1.0018E-06
2.0000E-02	.76000	1.0127E-06
3.0000E-02	.79000	1.1746E-06
2.5000E-02	.81500	1.4105E-06
1.5000E-02	.83000	1.5367E-06
1.0000E-02	.84000	1.9359E-06
1.0000E-02	.85000	1.9378E-06
1.5000E-02	.86500	2.5263E-06
3.0000E-02	.89500	3.2457E-06
2.0000E-02	.91500	3.3772E-06
1.5000E-02	.93000	5.7534E-06
1.0000E-02	.94000	5.9919E-06
1.5000E-02	.95500	6.3861E-06
3.0000E-02	.98500	1.0925E-05
1.5000E-02	1.0000	1.8731E-05

OUTPUT FROM HADES

COMPONENT FAILURE FREQUENCY DISTRIBUTION

COMPONENT: OFF-SITE POWER (OP)
CAUSE: SEISMICITY (SE)
NUMBER OF DOUBLETS: 45

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
2.5000E-02	2.5000E-02	7.2106E-06
5.0000E-02	7.5000E-02	8.1961E-06
2.5000E-02	.10000	9.6599E-06
2.5000E-02	.12500	1.2847E-05
1.0000E-02	.13500	1.2898E-05
5.0000E-02	.18500	1.4076E-05
2.5000E-02	.21000	1.5386E-05
2.5000E-02	.23500	1.7903E-05
5.0000E-02	.28500	1.9208E-05
2.0000E-02	.30500	2.0078E-05
2.5000E-02	.33000	2.0110E-05
1.0000E-02	.34000	2.0296E-05
2.5000E-02	.36500	2.3871E-05
5.0000E-02	.41500	2.5151E-05
2.5000E-02	.44000	2.5371E-05
1.0000E-02	.45000	2.6339E-05
2.0000E-02	.47000	3.0217E-05
1.0000E-02	.48000	3.1347E-05
1.0000E-02	.49000	3.3022E-05
2.5000E-02	.51500	3.3769E-05
2.5000E-02	.54000	3.3989E-05
5.0000E-02	.59000	3.5029E-05
2.0000E-02	.61000	3.8215E-05
1.5000E-02	.62500	4.0766E-05
1.0000E-02	.63500	4.3611E-05
1.0000E-02	.64500	4.4965E-05
2.0000E-02	.66500	4.6848E-05
1.0000E-02	.67500	5.5306E-05
2.0000E-02	.69500	6.0186E-05

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
1.5000E-02	.71000	6.5529E-05
3.0000E-02	.74000	6.5680E-05
1.0000E-02	.75000	6.6178E-05
1.0000E-02	.76000	8.2517E-05
1.5000E-02	.77500	8.6005E-05
1.5000E-02	.79000	8.8627E-05
3.0000E-02	.82000	9.8950E-05
1.5000E-02	.83500	1.0881E-04
1.5000E-02	.85000	1.2244E-04
3.0000E-02	.88000	1.2513E-04
1.5000E-02	.89500	1.4519E-04
1.5000E-02	.91000	1.4729E-04
3.0000E-02	.94000	1.5330E-04
1.5000E-02	.95500	1.7284E-04
3.0000E-02	.98500	1.9667E-04
1.5000E-02	1.0000	2.1033E-04

OUTPUT FROM HADES

CUT SET FAILURE PROBABILITY DISTRIBUTION

CUTSET ORDER: 1
1) COMPONENTS: ST
CAUSE: SEISMICITY (SE)
NUMBER OF DOUBLETS: 45

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
2.5000E-02	2.5000E-02	4.9398E-09
5.0000E-02	7.5000E-02	7.5653E-09
2.5000E-02	.10000	1.6301E-08
1.0000E-02	.11000	2.3725E-08
2.5000E-02	.13500	3.0005E-08
5.0000E-02	.18500	4.3241E-08
2.0000E-02	.20500	5.1542E-08
1.5000E-02	.22000	6.0360E-08
2.5000E-02	.24500	8.3278E-08
2.5000E-02	.27000	8.7234E-08
1.0000E-02	.28000	1.1413E-07
1.0000E-02	.29000	1.1950E-07
5.0000E-02	.34000	1.2069E-07
3.0000E-02	.37000	1.6111E-07
2.5000E-02	.39500	2.1478E-07
2.5000E-02	.42000	2.2520E-07
2.0000E-02	.44000	2.4601E-07
5.0000E-02	.49000	2.9944E-07
1.0000E-02	.50000	3.0500E-07
1.5000E-02	.51500	3.1704E-07
1.5000E-02	.53000	4.1532E-07
2.5000E-02	.55500	4.9218E-07
1.0000E-02	.56500	5.1710E-07
2.0000E-02	.58500	6.0310E-07
1.0000E-02	.59500	6.9130E-07
2.5000E-02	.62000	7.4489E-07
3.0000E-02	.65000	7.7671E-07
1.5000E-02	.66500	8.3337E-07
5.0000E-02	.71500	9.3755E-07
1.0000E-02	.72500	1.2178E-06
2.0000E-02	.74500	1.3104E-06
2.5000E-02	.77000	1.3769E-06

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
1.5000E-02	.78500	1.8187E-06
1.0000E-02	.79500	1.9029E-06
3.0000E-02	.82500	1.9174E-06
1.5000E-02	.84000	1.9451E-06
1.0000E-02	.85000	2.5343E-06
2.0000E-02	.87000	3.3876E-06
1.5000E-02	.88500	4.1690E-06
3.0000E-02	.91500	4.1941E-06
1.5000E-02	.93000	5.5764E-06
1.0000E-02	.94000	6.1351E-06
1.5000E-02	.95500	8.4204E-06
3.0000E-02	.98500	1.0938E-05
1.5000E-02	1.0000	1.9448E-05

OUTPUT FROM HADES

CUT SET FAILURE PROBABILITY DISTRIBUTION

CUTSET ORDER: 2
2) COMPONENTS: PTA PTB
CAUSE: SEISMICITY (SE)
NUMBER OF DOUBLETS: 45

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
2.5000E-02	2.5000E-02	1.5088E-21
5.0000E-02	7.5000E-02	5.6284E-21
2.5000E-02	.10000	5.7236E-20
1.0000E-02	.11000	1.3262E-19
1.5000E-02	.12500	6.3519E-19
2.0000E-02	.14500	8.7986E-19
1.0000E-02	.15500	5.9269E-18
3.0000E-02	.18500	7.9700E-18
2.5000E-02	.21000	2.0693E-17
5.0000E-02	.26000	6.3575E-17
1.5000E-02	.27500	9.5770E-17
2.5000E-02	.30000	4.6734E-16
1.0000E-02	.31000	1.0442E-15
2.5000E-02	.33500	1.6463E-15
5.0000E-02	.38500	4.2228E-15
1.5000E-02	.40000	5.6910E-15
2.0000E-02	.42000	6.0204E-15
2.5000E-02	.44500	2.2479E-14
1.0000E-02	.45500	3.5525E-14
2.5000E-02	.48000	4.5514E-14
1.0000E-02	.49000	4.8330E-14
3.0000E-02	.52000	5.6440E-14
5.0000E-02	.57000	9.6132E-14
2.0000E-02	.59000	2.3988E-13
1.5000E-02	.60500	2.9933E-13
2.5000E-02	.63000	3.5401E-13
1.5000E-02	.64500	5.2829E-13
1.0000E-02	.65500	7.2603E-13
1.0000E-02	.66500	1.2244E-12
2.5000E-02	.69000	1.6833E-12
3.0000E-02	.72000	2.3259E-12
5.0000E-02	.77000	2.7886E-12

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
2.0000E-02	.79000	2.9974E-12
1.5000E-02	.80500	5.1916E-12
2.5000E-02	.83000	6.3545E-12
1.0000E-02	.84000	1.2197E-11
1.0000E-02	.85000	1.2721E-11
1.5000E-02	.86500	1.6572E-11
3.0000E-02	.89500	3.0148E-11
2.0000E-02	.91500	3.8949E-11
1.5000E-02	.93000	1.0410E-10
1.0000E-02	.94000	1.2677E-10
1.5000E-02	.95500	1.5208E-10
3.0000E-02	.98500	4.0772E-10
1.5000E-02	1.0000	1.2558E-09

OUTPUT FROM HADES

CUT SET FAILURE PROBABILITY DISTRIBUTION

CUTSET ORDER: 2
3) COMPONENTS: DG OP
CAUSE: SEISMICITY (SE)
NUMBER OF DOUBLETS: 47

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
2.2384E-03	2.2384E-03	1.0106E-14
2.2384E-03	4.4768E-03	1.3668E-14
7.7598E-03	1.2237E-02	1.7536E-14
5.9691E-03	1.8206E-02	2.5081E-14
8.5060E-03	2.6712E-02	3.0287E-14
1.2684E-02	3.9396E-02	3.8996E-14
1.1341E-02	5.0737E-02	4.9813E-14
1.2087E-02	6.2825E-02	6.5249E-14
1.1610E-02	7.4435E-02	8.3993E-14
1.1938E-02	8.6373E-02	1.1086E-13
1.5281E-02	.10165	1.3972E-13
1.9250E-02	.12090	1.8301E-13
1.4415E-02	.13532	2.4112E-13
2.3041E-02	.15836	2.9804E-13
2.3787E-02	.18215	3.8972E-13
2.7547E-02	.20969	5.1070E-13
2.5548E-02	.23524	6.6395E-13
3.0174E-02	.26542	8.6975E-13
2.5578E-02	.29099	1.1088E-12
3.7426E-02	.32842	1.4325E-12
3.3427E-02	.36185	1.8797E-12
6.6227E-02	.42807	2.4702E-12
3.4501E-02	.46257	3.1618E-12
3.2800E-02	.49537	4.1717E-12
7.9866E-02	.57524	5.1855E-12
3.5277E-02	.61052	6.8312E-12
3.3487E-02	.64400	8.8655E-12
6.1899E-02	.70590	1.1231E-11
2.2891E-02	.72880	1.5090E-11
5.4975E-02	.78377	1.9826E-11
7.7598E-02	.86137	2.5272E-11
6.3869E-03	.86776	3.1890E-11

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
1.0565E-02	.87832	4.3043E-11
8.8044E-03	.88713	5.2895E-11
1.4415E-02	.90154	6.6908E-11
6.4466E-03	.90799	8.8792E-11
6.1929E-02	.96992	1.2348E-10
1.6117E-03	.97153	1.5710E-10
4.4768E-04	.97198	1.8094E-10
1.3431E-03	.97332	3.0229E-10
3.2233E-03	.97654	4.7124E-10
1.3968E-02	.99051	7.1755E-10
1.3431E-03	.99185	9.9442E-10
1.7012E-03	.99355	1.2455E-09
5.1036E-03	.99866	1.6110E-09
1.0744E-03	.99973	2.3438E-09
2.6861E-04	1.0000	3.9397E-09

OUTPUT FROM HADES

CUT SET FAILURE PROBABILITY DISTRIBUTION

CUTSET ORDER: 2
4) COMPONENTS: TK PTB
CAUSE: SEISMICITY (SE)
NUMBER OF DOUBLETS: 49

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
6.9476E-04	6.9476E-04	2.6141E-20
2.7790E-03	3.4738E-03	4.6814E-20
3.4738E-03	6.9476E-03	8.7806E-20
9.7266E-04	7.9203E-03	1.5966E-19
3.7517E-03	1.1672E-02	2.3956E-19
3.4738E-03	1.5146E-02	3.7357E-19
4.1686E-03	1.9314E-02	5.9615E-19
8.6150E-03	2.7929E-02	8.8060E-19
4.6966E-03	3.2626E-02	1.5387E-18
1.2645E-02	4.5271E-02	2.3902E-18
6.8920E-03	5.2163E-02	3.4890E-18
1.2784E-02	6.4946E-02	5.7247E-18
1.7647E-02	8.2593E-02	8.9129E-18
1.1700E-02	9.4293E-02	1.6077E-17
2.2149E-02	.11644	2.4815E-17
1.4951E-02	.13139	3.9393E-17
2.3677E-02	.15507	6.2813E-17
2.1037E-02	.17611	9.3558E-17
2.2649E-02	.19876	1.6039E-16
3.1486E-02	.23024	2.4713E-16
2.3455E-02	.25370	3.9927E-16
3.7183E-02	.29088	6.4634E-16
2.5206E-02	.31609	1.0162E-15
4.4687E-02	.36077	1.6847E-15
3.5210E-02	.39598	2.6458E-15
3.4321E-02	.43030	4.4802E-15
4.9411E-02	.47972	6.8361E-15
2.6651E-02	.50637	1.0765E-14
.10493	.61130	1.5103E-14
3.2459E-02	.64376	2.7749E-14
2.2566E-02	.66633	4.5651E-14
3.5905E-02	.70223	7.6415E-14

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
3.7739E-02	.73997	1.0647E-13
2.3344E-02	.76331	1.7473E-13
6.5585E-03	.76987	3.0477E-13
.10546	.87533	4.7962E-13
8.3371E-03	.88367	6.7460E-13
3.2848E-02	.91652	1.2745E-12
1.2117E-02	.92863	1.7606E-12
3.6683E-02	.96532	2.4477E-12
1.5174E-02	.98049	5.5184E-12
5.0023E-03	.98549	7.7653E-12
4.1686E-03	.98966	1.5797E-11
7.0865E-03	.99675	3.1355E-11
1.0005E-03	.99775	5.9336E-11
6.6697E-04	.99842	6.6799E-11
3.3348E-04	.99875	1.2749E-10
1.0005E-03	.99975	2.1424E-10
2.5011E-04	1.0000	4.1950E-10

SYSTEM UNAVAILABILITY

COMMON INITIATOR: SEISMICITY (SE)
NUMBER OF DOUBLETS: 16

FREQUENCY(PDF)	PROBABILITY(CDF)	FAILURE PROBABILITY
.16366	.16366	9.0736E-06
.13943	.30309	1.4205E-05
.23821	.54130	1.9117E-05
.14609	.68739	2.5185E-05
1.3773E-02	.70116	2.6448E-05
.25068	.95184	3.3486E-05
3.8904E-02	.99075	3.6964E-05
1.0259E-03	.99177	4.7017E-05
2.4201E-03	.99420	5.1043E-05
4.5158E-04	.99465	6.0308E-05
4.2966E-04	.99508	8.2629E-05
2.3774E-03	.99745	9.9862E-05
2.1110E-03	.99956	1.2549E-04
4.3404E-04	1.0000	1.5333E-04
1.3757E-06	1.0000	2.1036E-04
1.0066E-07	1.0000	2.2978E-04

**********THIS CONCLUDES THE OUTPUT FROM HADES**********

APPENDIX F: Published Papers and Interim Meeting Notes

F.1 Portchester Paper

APPLICATION AND EXTENSION OF THE MOCUS-BACFIRE2 COMMON CAUSE ANALYSIS CODE TO REACTOR SAFETY SYSTEMS

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ABSTRACT

A computer code MOCUS-BACFIRE2-BETA (MOBABE2) for quantitative common cause failure analysis (CCFA) is described in this paper. It uses the generic cause approach and the beta-factor method to identify and quantify common cause candidates of a system represented by a fault tree. The method for computing the reliability of redundant safety systems includes both independent and common cause failure types. The code is an extension of the qualitative CCFA code BACFIRE2 by incorporating the beta-factor method. Input to the programme consists of the system fault tree, common cause susceptibilities and reliability data parameters. A simplified Fire Protection System (FPS) is analyzed using the code to demonstrate the technique for quantitative CCFA. The results indicate common cause failures are the significant contributors to system unavailiability.

INTRODUCTION

Many methods [1, 2, 3, 4, 5] have been developed for quantitative common

cause failure analysis (CCFA). Most of the techniques available are limited to common mode failure analysis, i.e. systems consist of similar components or subsystems that are operated under the same environment. The objective of the development of the MOBABE2 code is to provide an effective CCFA code for analysis and evaluation of common cause failures in a complex system represented by a fault tree.

MOBABE2 is an extension of the qualitative CCFA code BACFIRE2 [6]. The synthesis procedure developed by Wagner [7] is used to identify common cause candidates. Then, for each common cause candidate, the total failure probability is calculated using the beta-factor method [1].

The purpose of this paper is to present a brief description of the theory and application of the MOBABE2 programme. A detailed description of the programme can be found in reference [8].

MOBABE2

MOBABE2 has the same structure as BACFIRE2. MOCUS [9], a cut set generating code, is used to determine the intermediate cut sets of the dissected fault trees and stores the results in specified logical units. The Wagner synthesis procedure is used to determine common cause candidates. The failure probability of each common cause candidate at a common location is calculated and compared with the cutoff probability (threshold probability). Common cause candidates are removed from the list if their failure probabilities are less than the cutoff value. The list of common cause candidates at a common location were outputted. The same procedures are carried out for each common location. The programme algorithm is summarized in Figure 1.

Generic Cause Approach [10]

The generic cause approach is employed to identify common cause candidates. The qualitative failure characteristics for each component event in each minimal cut set are examined. In order to be identified as a common cause candidate, all the basic events of the minimal cut set must have a common susceptibility located in a common location of that secondary cause. In some cases, a minimal cut set can be identified as a common cause candidate based on a common condition, called a common link. A common link is a dependency among components and cannot be removed by a physical barrier, e.g. a common energy source or maintenance procedure.

Synthesis Procedure [7]

The procedure used in BACFIRE2 circumvents the problem of determining all the hardware minimal cut sets from the fault tree by dissecting the fault tree

and determining the minimal cut sets for individual branches and then synthesizing common cause failure analysis results for the TOP event. The minimal cut sets found for the individual branches of the dissected fault tree are called intermediate minimal cut sets. Common cause failure analysis of the intermediate minimal cut sets yields intermediate common cause candidates for that particular branch of the fault tree. The dummy event contains all the information necessary for analysis of the next level of the fault tree. At the completion of the analysis, the dummy events are expanded and common cause candidates for the TOP event are constructed.

Definition of the Beta Factor

The beta factor of a component event is the fraction of all common cause failures to the total number of failures, which include both independent and common cause failures. Since most components are susceptible to more than one common cause, the level of susceptibility is used to specify the relative occurrences of a secondary failure of a component.

Mathematical Model

The common cause candidates identified can be considered as a subsystem. To quantify the common cause candidates, the Markov processes is used to model these subsystems. The failure and repair rates are assumed to be exponentially distributed. A non-identical repairable two-component system with common cause failure is used as an example. The Markov state transition diagram is shown in Figure 2. The following assumptions are made to develop the model:

1) common cause and independent failures are statistically independent,
2) common cause failures can only occur with more than one unit, and they fail simultaneously.

The system of first order differential equations can be written for the model as:

$$P_0'(t)=-\left(\sum_{i=1}^{2}\lambda_i(t)+\lambda_c(t)\right)P_0(t)+\sum_{i=1}^{3}P_i(t)\mu_i(t) \quad (1)$$

$$P_1'(t)=-(\lambda_2(t)+\mu_1(t))P_1(t)+P_3(t)\mu_2(t)+P_0(t)\lambda_1(t) \quad (2)$$

$$P_2'(t)=-(\lambda_1(t)+\mu_2(t))P_2(t)+P_0(t)\lambda_2(t)+P_3(t)\mu_2(t) \quad (3)$$

$$P_3'(t)=-\left(\sum_{i=1}^{2}\mu_i(t)+\mu_3(t)\right)P_3(t)+\sum_{i=1}^{2}P_i(t)\lambda_{(3-i)}(t)+P_0(t)\lambda_c(t) \quad (4)$$

$$\sum_{i=1}^{3}P_i(t)=1 \quad (5)$$

If all the failure and repair rates are time independent and a set of appropriate boundary conditions are given, equations (1) to (5) are then a set of linear differential equations which can be solved by using Laplace transform techniques. The system unavailability at time t is $P_3(t)$.

Beta-Factor Method [11, 12]

The total failure rate for each unit, λ, is assumed constant with time and can be expanded into its independent and common cause components:

$$\lambda = \lambda_i + \lambda_c \tag{6}$$

where λ_i is the unit failure rate for independent causes, and
λ_c is the unit failure rate for common cause.

The component parameter beta is defined as the fraction of the total failure rate attributable to common cause failures:

$$\beta = \lambda_c / \lambda \tag{7}$$

For the same Markov model presented in the previous section, if the following assumptions are made, then the system model can be simplified as shown in Figure 3:

1) constant failure rates with time t,
2) consider non-repairable components only, and
3) at time t=0, both units are operable,
   i.e. $P_0(t=0)=1$ and $P_i(t=0)=0$, for i=1,2,3.

The system of differential equations for the model are:

$$P_0'(t) = -(\lambda_1+\lambda_2+\lambda_c)P_0(t) \tag{8}$$
$$P_1'(t) = -(\lambda_2+\beta_2\lambda_2)P_1(t)+\lambda_1 P_0(t) \tag{9}$$
$$P_2'(t) = -(\lambda_1+\beta_1\lambda_1)P_2(t)+\lambda_2 P_0(t) \tag{10}$$
$$P_3'(t) = \lambda_c P_0(t)+(\lambda_2+\beta_2\lambda_2)P_1(t)+(\lambda_1+\beta_1\lambda_1)P_2(t) \tag{11}$$

The system unavailability at time t to the second order is:

$$F(t) = P_3(t) = \lambda_c t + \lambda_1\lambda_2 t^2 + \lambda_1\lambda_2(\beta_1+\beta_2)\frac{t^2}{2} - \ldots \tag{12}$$

=Pr(common cause failure) + Pr(random failures) +
Pr(partial common cause failures) + truncation errors

Generalized to a non-identical and non-repairable n-component system:

$$F(t) = \lambda_c t + \sum_{i=1}^{n}\lambda_i t^n + \sum_{j=1}^{n}\lambda_j t \sum_{\substack{i=1\\ i\neq j}}^{n} \beta_i\lambda_i t^{(n-1)} + \ldots \tag{13}$$

Data Parameters for Beta-Factor Method

The major advantage of using the beta-factor method to quantify common

cause candidates is the model parameters are readily available from existing data bases. Consider an operating time period, T, during which data has been collected from each of the N systems where each system consists of two components of the same type:

$$\lambda = \frac{1}{2NT} \sum_{i=1}^{N} (n_{i1}+n_{i2}+2n_{ic}) \tag{14}$$

$$\lambda_c = \frac{1}{2NT} \sum_{i=1}^{N} 2n_{ic} \tag{15}$$

$$\beta = 2 \sum_{i=1}^{N} n_{ic} \Big/ \sum_{i=1}^{N} (n_{i1}+n_{i2}+2n_{ic}) \tag{16}$$

where n_{i1} = number of random failure of component 1 in system i,
n_{i2} = number of random failure of component 2 in system i, and
n_{ic} = number of common cause failure.

Estimations of beta factor for different component types obtained from reliability experience data are found to have values very closely clustered in the range from 0.1 to 0.2 [11, 12]. Therefore component types with unknown betas can be easily approximated. For minimal cut sets with more than two units, the beta factor model assumes that all units fail if a common cause failure occurs. The method is most useful for analyzing common cause failures in systems with limited redundancy, two or three units. The value β_{cs} for a minimal cut set with different components cannot be estimated from data directly due to the large number of different combinations of component types. However cross-component dependencies can generally be neglected.

When individual failure probabilities of each cut set are calculated, the system failure probability (unavailability) can be calculated as a function of the failure probabilities of different cut sets, C_i:

$$F(S) = \sum_i Pr(C_i) - \sum_{i \neq j} Pr(C_i \cap C_j) + \ldots + (-1)^{m-1} Pr(C_1 \cap C_2 \ldots \cap C_m) \tag{17}$$

APPLICATION

The MOBABE2 code was used to perform a CCFA on a simplified version of the Fire Protection System of Millstone 1 BWR. The sample problem flow diagram is in Figure 4; Figure 5 contains the system fault tree. The fault tree consists of 14 gates and 23 component events; 5 maps were used; a maximum size of 3 is specified for the cut sets; a cutoff probability was set at 10^{-7} and mission time was ten hours. 344 common cause candidates were identified, of which 2 cut sets had 1 component and 4 cut sets had 2 components and the rest were 3-component cut sets. The system unavailability was estimated to be 10^{-4}.

CONCLUSIONS

The code can carry out meaningful quantitative common cause failure analysis (CCFA) even with limited data available. Experience with the code is limited to standby reactor safety systems. As data available for CCFA improves both qualitatively and quantitatively, more sophisticated methods can be used for common cause failure analysis.

ACKNOWLEDGMENTS

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12. K. N. Fleming, "A Reliability Model for Common Mode Failures in Redundant Safety Systems", Proc. of the Sixth Annual Pittsburgh Conference on Modelling and Simulation, GA Report: GA-A 13284 (1975).

FIGURE 1 FLOW CHART FOR MOBABE2

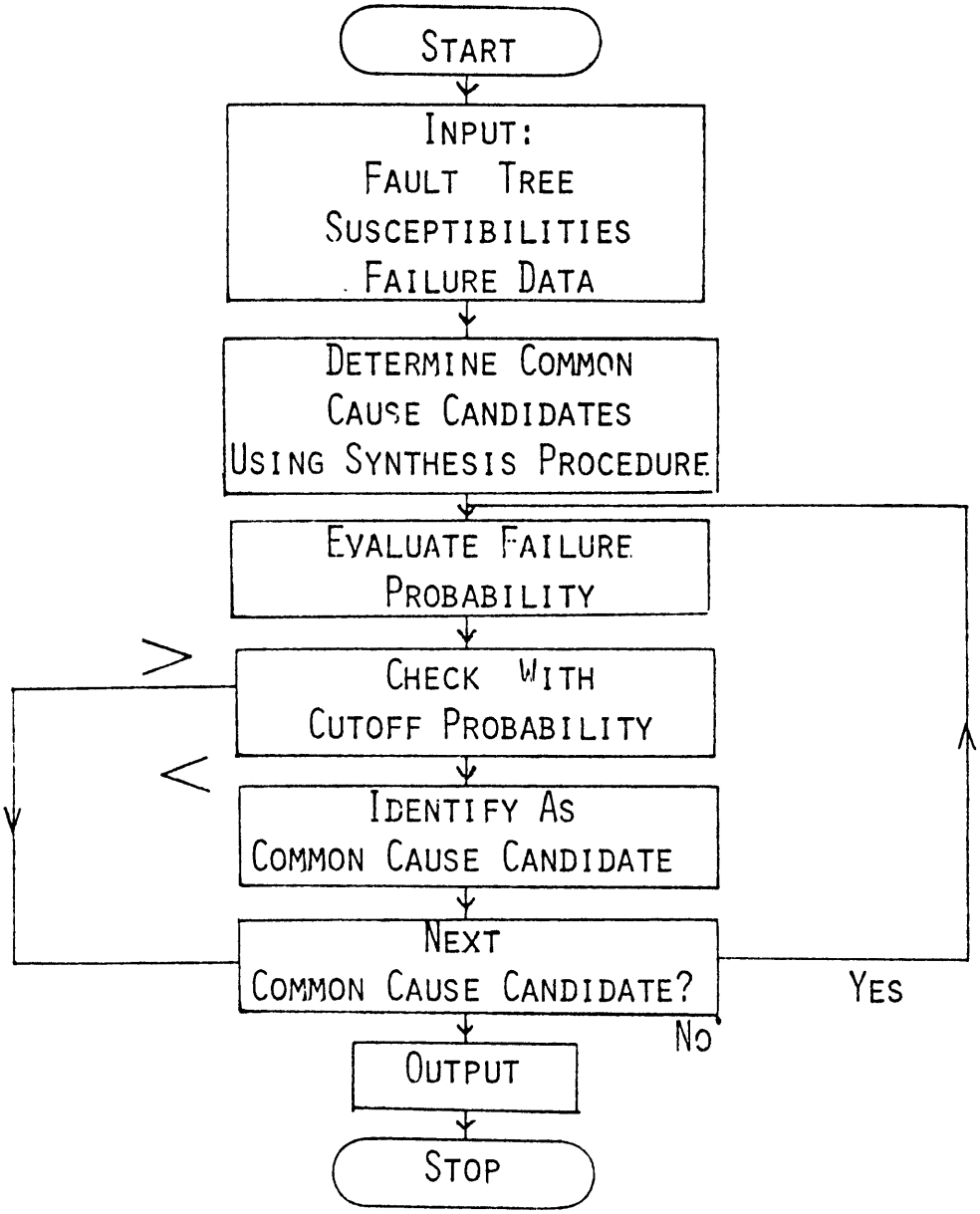
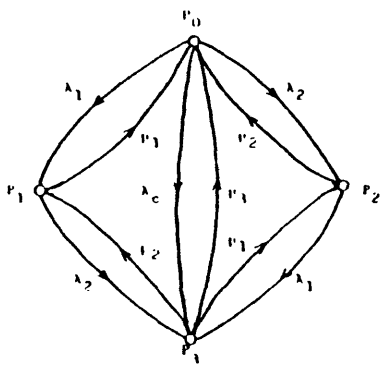


Figure 2 State Transition Diagram For Repairable 2-Component System



$P_0(t)$ = probability at time t, both units are operational

$P_i(t)$ = probability at time t, only unit i has failed, for i = 1, 2

$P_3(t)$ = probability at time t, both units have failed

λ_i = independent failure rate of unit i, for i = 1, 2

λ_c = common cause failure rate

μ_i = repair rate of unit i, for i = 1, 2

μ_3 = repair rate of both units 1 & 2

Figure 3 State Transition Diagram For Non-Repairable 2-Component System

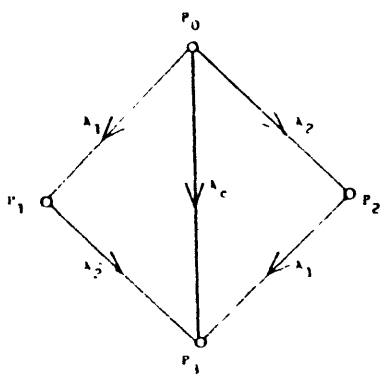


Figure 4 Sample Problem Flow Diagram

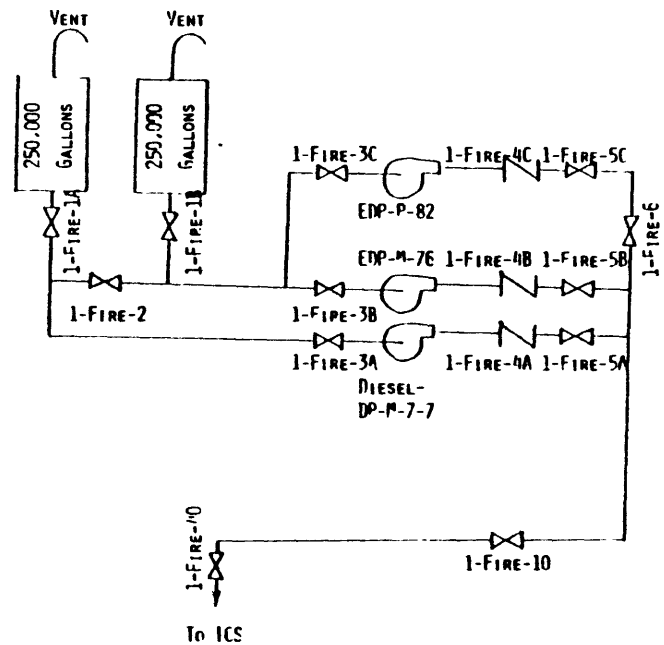
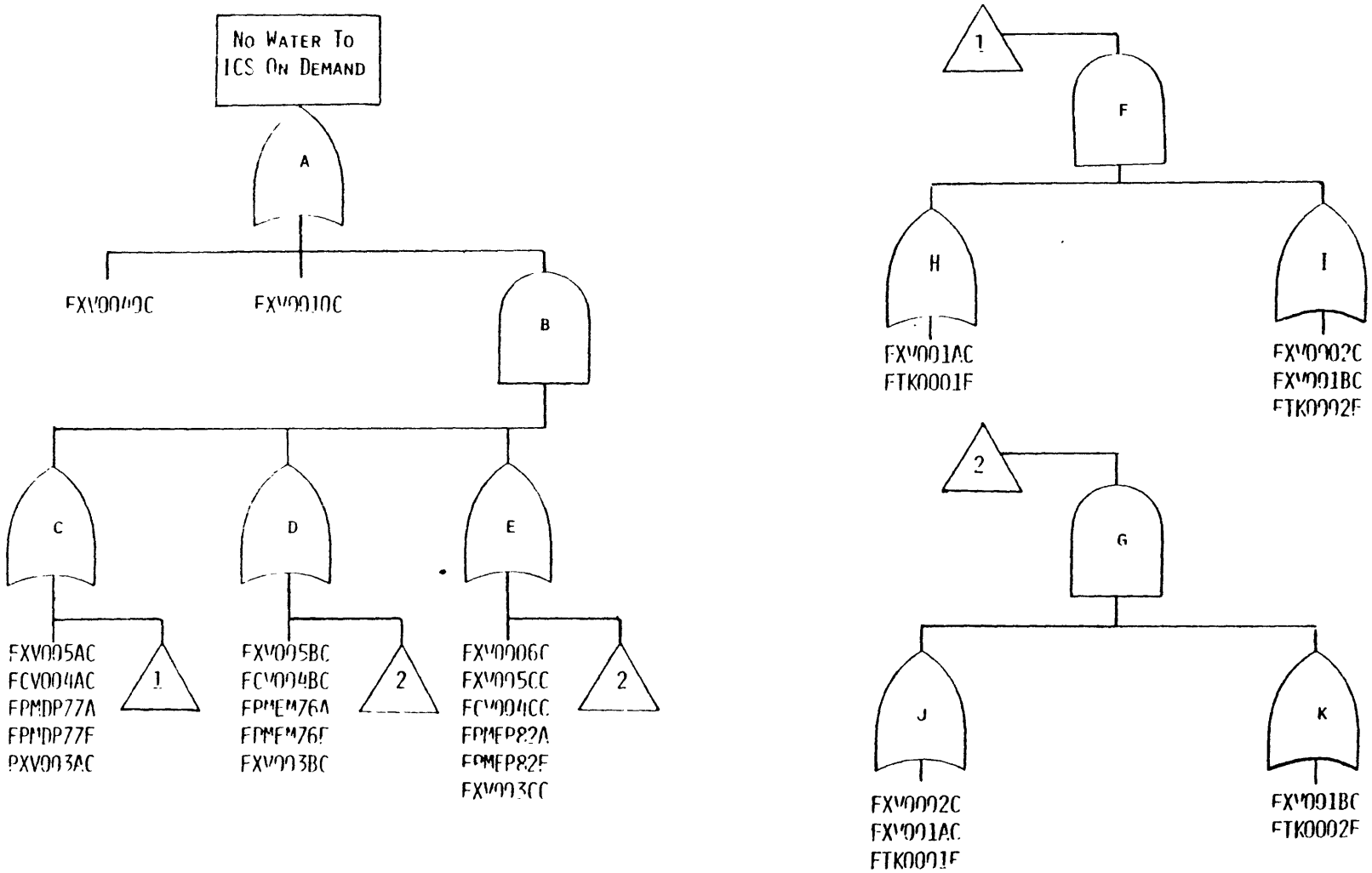


FIGURE 5 SYSTEM FAULT TREE



F.2 Interim Meeting Notes

F.2.1 Progress Review Meeting, March 3, 1982

PROFESSOR CAROLYN D. HEISING
NUCLEAR ENGINEERING DEPARTMENT
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 23, 1982

Dear Project Sponsor:

On March 3, 1982 we will be reviewing the status of the common cause analysis project at M.I.T. Attached is a progress report that details the progress of this project. We are far along in the accomplishement of the five tasks orginally defined in our proposal. We believe the new code we have developed (MOBABE) will be a useful tool for utilities involved in system reliability calculations. We hope to discuss with you how to make our work more amenable for use in probabilistic risk assessments (PRAs) as well.

Publications sponsored on this project to date include:

(1) Mak, C., "Assessment and Comparison of Qualitative Common Cause Failure Analysis Codes", S.M. Thesis, Nuclear Engineering Department, M.I.T., August, 1981.

(2) Heising, C.D., Karimi, R., Mak, C., Modarres, M., Rasmussen, N.C., and Wolf, L., User's Manual for MOCUS-BACFIRE: A Computer Program for Common Cause Failure Analysis, MIT-EL-81-037, Electric Utility Program, November, 1981.

(3) Mak, C., Heising, C., and Modarres, M., "Application and Extension of the MOCUS-BACFIRE Common Cause Analysis Code to Reactor Safety Systems", Session IV-B, Common Mode Failures, International ANS/ENS Topical Meeting on Probabilistic Risk Assessment, Port Chester, New York, September 20-24, 1981.

Publications in progress include:

(1) Mak, C., "Improved Methods for Common Cause Analysis", Engineer's Thesis, Nuclear Engineering Department, M.I.T., expected June 1982.

(2) MOBABE User's Manual, expected June 1982 (represents update of User's Manual listed above).

(3) Technical paper for publication in Reliability Engineering journal (by August 1982).

Additionally, we are using the MOBABE code for sample problem applications in the M.I.T. course 22.40: "Advanced Reliability Analysis and Risk Assessment".

We hope you will give us your feedback on our progress.

Sincerely,

Carolyn

Carolyn D. Heising
Principal Investigator
Common Cause Project

CDH/sc

Energy Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
E40-479
(617) 253-6659

February 23, 1982

MEMORANDUM

TO: Mr. Raymond Bagley, Northeast Utilities Service Co.
Mr. Robert Krauss, PSE&G Research Corp.

FROM: Barbara Duffney, Administrative Assistant, Electric Utility Program Barbara Duffney

SUBJECT: Progress Report for the Project: "Common Cause Analysis: A Review and Extension of Existing Methods"

Enclosed please find the subject report. This report will be discussed during the progress review meeting scheduled for Wednesday, March 3, 1982 (Ref. my memo to you dated January 28, 1982).

If you have any questions about the report or the meeting, please don't hesitate to call me at the number listed above.

We look forward to seeing you on March 3.

Enclosure
xc: Prof. C. Heising
Dr. W. Hinkle
Prof. N. Rasmussen

Energy Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
E40-473
(617) 253-4241

January 28, 1982

MEMORANDUM

TO: Mr. Raymond Bagley, Northeast Utilities Service Co.
Dr. Jerald Holm, Northeast Utilities Service Co.
Mr. Robert Krauss, PSE&G Research Corp.

FROM: Barbara Duffney, Administrative Assistant, Electric Utility Program

SUBJECT: Progress Review Meeting for the Project: "Common Cause Analysis: A Review and Extension of Existing Methods"

This memo confirms our telephone conversations regarding the subject meeting.

The meeting will be at MIT on Wednesday, March 3, 1982 in Room E40-464 beginning at 12:00 p.m. with lunch at the Faculty Club (E52-6th floor). The meeting will end at approximately 4:00 p.m.

Enclosed please find a map of the campus which shows the location of the meeting room, parking accomodations, and the Faculty Club. The progress report for this meeting will be mailed to you by or before February 22, 1982. If you have any questions concerning the meeting, please don't hesitate to call me at the number listed above.

Enclosure
xc: Prof. C. Heising
Dr. W. Hinkle
Mr. K. Matson
Prof. N. Rasmussen

Ray Bagley
Robert Krauss
Bill Hinkle

JOHN P. RANKIN
ENGINEERING SERVICES & SUPPORT MANAGER

THE BOEING COMPANY
P.O. Box 58747, Houston, Texas 77058
Tel. (713) 486-1259

Common Cause Failure Analysis

Progress Report

February 1982

Nuclear Engineering Department

Massachusetts Institute of Technology

Richard C. Tardiff

The First Progress Report

We've had the job a month now
And think that you will find
We have a lot of reasons
To be a month behind.

When you gave us the contract
You multiplied our cares;
We had to stick it in with
Two other big nightmares.

This should be no deterrent
The progress will be fine
When everyone stops laughing
They'll start on the design.

The man who did the runout
Erred and was moved up higher
Our forecasts now look better
'Cause we have a bigger liar.

IEEE Reliability Society
Newsletter, September 1981.

COMMON CAUSE ANALYSIS: A REVIEW AND EXTENSION OF EXISTING METHODS

Carolyn D. Heising, Principal Investigator
Cho Mak, Research Assistant

I. Introduction

The objective of this study is to evaluate and assess existing common cause failure analysis methods, and to develop a computer program for analysis and evaluation of common cause failures of a system represented by a fault tree.

The project (1) is structured into five tasks as summarized below (see Figure 1 ; current status is shown):

TASK 1: Assessment of existing qualitative common cause failure analysis codes that use the generic cause approach to identify common cause candidates from minimal cut sets.

TASK 2: Choose an appropriate quantitative method to quantify the common cause candidates and evaluate the system unavailability.

TASK 3: Implementation of the computer code using the methodology developed above and use the simplified sample problem to verify that the code is operational.

TASK 4: Review and further extend the capabilities of the code to include uncertainty analysis, data collection and interpretation; re-define parameters and failure criteria.

TASK 5: Use the final version of the code for a detailed common cause failure analysis.

Task 1	Task 2	Task 3	Task 4	Task 5
Comparison and Assessment of Qualitative CCFA Codes Using the Generic Cause Approach.	Comparison and Assessment of Quantitative CCFA Methodologies.	Implementation of the Quantitative Method Chosen to Quantify Common Cause Candidates and Evaluate System Unavailability.	Review and Further Extend the Capabilities of the Code. Data Collection and Interpretation.	Conduct a Detailed CCFA Using the Final Version of the Code.
Status:				
April 1981	May 1981	August 1981	February 1982	To be completed
Completed	Completed	Completed	in progress	by June 1982

Figure 1: Summary of the Project (1).

II. Review of Tasks 1-3 (February 1981 - August 1981)

2.1 The Qualitative CCFA Technique: Generic Cause Approach

The minimal cut sets of the fault tree were identified and the qualitative failure characteristics for each basic event in each minimal cut set were examined. If all of the basic events of the minimal cut set are susceptible to a secondary cause and are located in a common location, or if all of the basic events have a common link, the minimal cut set is then identified as a common cause candidate.

For most complex systems, determining all of the minimal cut sets is often a difficult if not impossible task. (These will be reviewed in our March 3 presentation.) Two methods have been developed by researchers to circumvent these difficulties.

2.2 COMCAN 2:EG&G (3): The code uses the susceptibility tree technique to construct a susceptibility tree for each common location. The susceptibility trees only contain basic events that are located at that particular domain and are susceptible to that cause. The minimal cut-sets determined for each susceptibility tree are the common cause candidates for that common location . Since the size of the susceptibility tree is generally much smaller than the original fault tree, this makes determination of minimal cut sets of any order much faster.

The code had been extended to COMCAN 3 (5) where a useful parameter was defined. The component importance is the ratio of the sum of unavailabilities of all common cause candidates that include this component to the total system unavailability. Components which are major contributors to system unavailability can be easily identified. Unfortunately, the code is written for a CDC computer and can only handle qualitative CCFA. Only independent failures are considered in calculating the unavailabilities

of the minimal cut sets and the system unavailability. These numbers are inconsistent with the CCFA and may be nonconservative. (6)

2.3 BACFIRE 2
Fussell (4): The synthesis method is used to avoid the need to determine all minimal cut sets. The fault tree is dissected into branches and dummy events are assigned as top events for the sub-trees. Intermediate minimal cut sets are determined and intermediate common cause candidates are identified. The common cause candidates are then constructed by resolving the dummy events. (8)

2.4 MOBABE MIT (9): A cut-set generating code (MOCUS) has been added to BACFIRE2 and the Beta-Factor method is incorporated to quantify the common cause candidates identified. The Beta-Factor method is a parametric model for inter-component dependencies developed by Karl Fleming (10). Each basic event failure is assumed exponentially distributed and has total failure rate λ constant with time:

$$\lambda = \lambda_i + \lambda_c \tag{1}$$

where

λ_i = failure rate for independent causes, and

λ_c = failure rate for common causes.

The component parameter β is defined as

$$\beta = \lambda_c / \lambda \tag{2}$$

The Beta Factor method was chosen to quantify common cause candidates because parameters necessary for the analysis are readily available from the literature. Beta factors for different component types are found to have values between 0.1 to 0.2. Usually, a default value of 0.1 is assigned to component beta factors which are unknown.

A simplified AFWS and FSP have been used as sample problems, as described in Cho Mak's S.M. thesis.

III. Review of Task 4 (in progress)

The MOBABE code has been under constant improvement and development since last fall. Several features have been or are being added to extend the capability of the program.

3.1 Uncertainty Analysis (11)

In interpreting the results of a risk and/or reliability analysis, there will often be considerable uncertainty associated with the estimation of the overall system unavailability. The sources of this uncertainty can arise from modelling uncertainties and/or data uncertainties. There are several methods to estimate the propagation of uncertainties (as discussed by Mazundar(12)). Only the Monte Carlo method is applicable in our case because the distribution of the input variables are known. Other analytic techniques (e.g., linearization, method of moments and numerical integration) require a prior knowledge of the top event distribution. Moreover, no analytic technique can handle partially correlated input/coupled events/dependent events (i.e., common cause failures). Vicki Bier of M.I.T. (13) put an upper bound on the uncertainty by assuming that all coupled failures are totally correlated events, and then used the method of moments for propagation of uncertainties in the fault tree. However, this approach is not readily applicable to MOBABE.

The major drawback of the Monte Carlo simulation is the large number of simulations necessary for rare events. A Monte Carlo method has been implemented in MOBABE and sample problems have been run using the uncertainty analysis capability of the code.

3.2 Continuous or Discrete Distributed Functions

In order to handle common cause initiators which are external events (earthquake, etc.) the fragility function of the components is necessary for the analysis. The Beta Factor method may no longer be a pointwise estimate but a probability distribution function which is a function of both the fragility curve and the frequency-intensity curve of the common cause. This type of analysis can be simplified by using discrete probability distribution analysis. We are continuing to examine the development of a separate algorithm which can generate Beta factors to be input into the MOBABE code. It may well be that Beta functions need be specified.

3.3 Data Collection and Interpretation

Data collection and interpretation is a very crucial part of any common cause analysis. With our limitations of time and resources, direct data collection and interpretation from raw data sources has not been possible. Therefore, extreme care must be taken to ensure that data from the available literature is compatible with our model; subjective judgement must be given sparse data and the associated large uncertainties.

IV. TASK 5: (to be completed by the end of June 1982)

To gain experience and insight on both the limitations and flexibility of the MOBABE code, a realistic reliability analysis of a safety system with the cooperation of the utilities will be conducted. We ask for your suggestions of a suitable system to analyze.

V. Conclusions/Recommendations for Further Work

It has to be emphasized that the methodology developed here in the MOBABE code is suitable for certain types of dependent failure analysis and ~~risk assessments~~ (e.g., common cause initiators, intersystem physical interactions, etc.). A more detailed discussion on CCF by Karl Fleming can be found in Ref (14). Within the overall framework of PRA development, however, techniques for other

types of dependent failure analysis are urgently needed (e.g. sneak circuit analysis, especially in the areas of large system interactions, and human interactions, etc.). We suggest that some of our remaining effort be shifted to these areas as we near the completion of this project. Moreover, this is an area we expect will require further work and we expect to propose to you a project in the area of common cause analysis techniques for power plant PRAs.

References

(1) Heising, C.D., "Common Cause Project", Proposal, Nuclear Engineering Department, MIT, Cambridge, Massachusetts, February 1981.

(2) Burdick, G.R., et al, COMCAN- A Computer Program for Common Cause Analysis, AMCRO1314, May 1976.

(3) Rasmuson, D.M. et al, COMCAN 2-A Computer Program for Common Cause Analysis, TREE-1289, September 1978.

(4) Rasmuson, D.M.,et al, COMCAN 2A- A Computer Program for Common Cause Failure Analysis, TREE-1289, September 1978.

(5) Rasmuson, D.M.,et al, COMCAN 3- A Computer Program for Common Cause Analysis, to be published April 1982.

(6) Rasmuson, D.M.,et al, A Common Cause Failure and Unavailability Analysis of the McGuire Unit 2 AFS, EGG-IS-5545, September 1981.

(7) Rooney, J.J. and J.B. Fussell, BACFIRE 2- A Computer Program to Aid in Common Cause Failure Analysis of Complex Systems, University of Tennessee, August 1978.

(8) Wagner, D.P. et al, Common Cause Failure Analysis of Complex System, SIAM, June 1977.

(9) MOBABE - User's Manual, MIT, Nuclear Engineering Department, Cambridge, Massachusetts, September 1981.

(10) Fleming, K.N., "A Reliability Model for Common Cause Failures in Redundant Systems", Proceedings of the Sixth Annual Pittsburgh Conference on Modelling and Simulation, April 1975.

(11) Parry, G.W., The Characterization and Evaluation of Uncertainty in Probabilistic Risk Analysis, SRD-R-190, United Kingdom Atomic Energy Authority, October 1980.

(12) Mazumdar, M., et al, "Propagation of Uncertainties in Problems of Structural Reliability," Nuclear Engineering and Design, 50(1978).

(13) Bier, Vicki, An Exploration and Extension of Analytic Methods for Propagation of Variances in Fault Trees, MIT, Ph.D. Thesis, Operations Research Department, 1982.

(14) Fleming, K.N., "Proposal - A Study of Common Cause Failures", PLG-P149, Pickard, Lowe and Garrick, Inc., January 1982.

-M.I.T. COMMON CAUSE ANALYSIS PROJECT-

PROJECT OVERVIEW AND STATUS REPORT

PROFESSOR C. HEISING

NUCLEAR ENGINEERING DEPARTMENT

MARCH 3, 1982

REVIEW OF PROJECT TASKS

TASK 1: ASSESSMENT OF EXISTING QUALITATIVE COMMON CAUSE FAILURE ANALYSIS CODES THAT USE GENERIC CAUSE APPROACH TO IDENTIFY COMMON CAUSE CANDIDATES FROM MINIMAL CUT SETS

- COMCAN VERSIONS
- BACFIRE VERSIONS
- SETS (SANDIA)

STATUS: COMPLETED APRIL 1981

CONCLUSION: BACFIRE IS PREFERABLE OVER THE OTHERS, AND IS THE CODE SELECTED FOR INTEGRATION WITH QUANTITATIVE EVALUATION METHODS

TASK 2: CHOOSE AN APPROPRIATE QUANTITATIVE METHOD TO QUANTIFY THE COMMON CAUSE CANDIDATES AND EVALUATE THE SYSTEM UNAVAILABILTY

STATUS: COMPLETED MAY 1981

CONCLUSIONS: BETA-FACTOR METHOD DEVELOPED BY KARL FLEMING AT GENERAL ATOMIC FOR HTGR-PRA IS PREFERABLE. THIS METHOD WAS INTEGRATED INTO THE MODIFIED BACFIRE PACKAGE. (IT HAS ALSO BEEN REFINED AND UPDATED).

PRODUCT: MOBABE CODE
(MOCUS - BACFIRE - BETA FACTOR METHOD)

TASK 3: IMPLEMENTATION OF THE QUALITATIVE METHOD CHOSEN TO QUANTIFY COMMON CAUSE CANDIDATES AND EVALUATE SYSTEM UNAVAILABILITY

STATUS: COMPLETED AUGUST 1981

CONCLUSIONS: SAMPLE PROBLEMS WERE RUN USING THE MOBABE CODE. THESE INCLUDED ANALYSES OF THE FOLLOWING TWO SYSTEMS:

- °AUXILIARY FEEDWATER SYSTEM (AFWS)
- °FIRE PROTECTION SYSTEM (FPS)

DOCUMENTATION:

- °CHO MAK'S SM THESIS
- °PAPER FOR PORTCHESTER PRA MEETING

PRODUCT: USEFUL EXAMPLES TO GUIDE UTILTY EFFORTS IN SYSTEMS ANALYSIS.

TASK 4: REVIEW AND FURTHER EXTEND THE CAPABILITIES OF THE CODE TO INCLUDE UNCERTAINTY ANALYSIS, DATA COLLECTION AND INTERPRETATION; RE-DEFINE PARAMETERS AND FAILURE CRITERION.

STATUS: IN PROGRESS FEBRUARY 1982

PROJECTED DATE OF COMPLETION

END OF MARCH 1982

PRELIMINARY CONCLUSIONS:

- °MONTE CARLO METHOD APPLICABLE
- °HAS BEEN INCORPORATED INTO MOBABE
- °SAMPLE PROBLEMS ARE BEING RUN

FURTHER WORK NEEDED (BEYOND THIS PROJECT SCOPE):

- °MORE EFFICIENT METHOD REQUIRED TO REDUCE COMP. TIME

TASK 5: USE OF FINAL VERSION OF THE CODE FOR A DETAILED COMMON CAUSE FAILURE ANALYSIS

STATUS: IN PROGRESS

PROJECTED DATE OF COMPLETION:

END OF JUNE, 1982

★ SUGGESTIONS NEEDED FOR SYSTEM TO BE ANALYZED ★

FINAL PRODUCT: REVISED CODE ON TAPE FOR USE IN IBM-370 SYSTEM

DOCUMENTATION: UPDATED FINAL CODE USER'S MANUAL

CHO MAK'S ENGINEER'S THESIS

TECHNICAL PAPER TO BE SUBMITTED TO RELIABILITY ENGINEERING JOURNAL

-M.I.T. COMMON CAUSE ANALYSIS PROJECT-

APPLICATION OF STUDY RESULTS TO NPP RISK ASSESSMENTS: FUTURE PLAN

PROFESSOR C. HEISING

NUCLEAR ENGINEERING DEPARTMENT

MARCH 3, 1982

°BENEFITS OF PRESENT WORK:

°EMPHASIS HAS BEEN ON CODE DEVELOPMENT PRIMARILY FOR UTILITY SYSTEMS RELIABILITY ANALYSIS

°ADVANTAGES:

CODE PROVIDES SYSTEMATIC FRAMEWORK FOR PERFORMING A DETAILED ANALYSIS OF SYSTEM AVAILABILITY (POINT ESTIMATE PLUS UNCERTAINTY BOUNDS)

°DISADVANTAGES:

USE OF SUCH DETAILED INFORMATION IN A PRA MAY NOT BE NECESSARY.

°A SIMPLIFIED APPROACH TO CCFA MAY BE MORE DESIRABLE IN A FULL-SCALL UTILITY PRA FOR REASONS OF REDUCED COST AND ENHANCED USE OF THE AVAILABLE DATA

° DIRECTIONS FOR FUTURE WORK:

° FOCUS ON UTILITY PLANT-SPECIFIC PRA'S

METHODS FOR CCFA WILL BE BROADER AND MORE SIMPLIFIED

° PROPOSED METHODOLOGICAL APPROACH

CAUSE-TABLE APPROACH --(CAUSE TABLE - DPD)

° THIS IS THE SIMPLIFIED FAULT TREE ANALYSIS METHOD USED IN THE Z/IP STUDIES

° BENEFIT TO UTILITY IS REDUCED COST AND MORE MANAGEABLE FAULT TREES

° CAUSE TABLE REQUIRES FULL DETAILED UNDERSTANDING OF SYSTEM, MUST INCORPORATE EXPERT JUDGEMENT INTO NUMERICAL EVALUATIONS

TABLE 3-1. EXAMPLE CAUSE TABLE FOR CAUSES AFFECTING SINGLE AND MULTIPLE COMPONENTS

SYSTEM: Sample
COMPONENTS: A, B, C, D, E, F, G
MINIMAL CUTSETS: A, D, BC, EFG

Part I - Accident Sequence Dependent Boundary Conditions			
Initiating Event	Accident Sequence	Interfacing Systems Failures and Boundary Conditions	Changes in Internal and External Environment

Part II - Single Failure Cause Sets							
Cause Category	Components						
	A	B	C	D	E	F	G
Hardware Environmental Test Maintenance Operator Error Other							

Part III - Multiple Failure Cause Sets					
Cause Category	Component Failure Sets				
	BC	EF	FG	EG	EFG
Human Interactions Design Error Manufacturer/ Installation Error Operator Error Test/Maintenance Error Physical Interactions Excessive Temperature Excessive Pressure Excessive Vibration Excessive Impact Corrosive Agent Excessive Moisture Other					

TABLE 3-2. DEPENDENT FAILURES ASSOCIATED WITH A CAUSE TABLE TYPE OF SYSTEMS ANALYSIS

I. Accident Sequence Dependent Boundary Conditions
A. Failures of Interfacing/Support Systems (shared equipment dependencies in Table 1-2) B. Sequence Dependent Environmental Changes C. Sequence Dependent Exceedance of System Operating Limits D. Other
II. Common Cause Failures
A. Human Interactions 1. Design Error 2. Manufacturing/Installation Errors 3. Operator Errors 4. Test/Maintenance Errors B. Physical Interactions (excessive environmental stresses) C. Other
III. Multiple Failures Resulting from Different but Dependent Causes
A. Propagating Failures B. Technical Specification Dependencies C. Other

°DPD METHOD FOR EXTERNAL EVENT ANALYSIS:

°REFINE DPD METHOD USED FOR EXTERNAL EVENT ANALYSIS TO EXTEND TO OTHER TYPES OF COMMON CAUSE EVENTS (E.G.; HUMAN ERROR, ENVIRONMENTAL FACTORS: CORROSION, DEGRADATION, ETC.)

ADVANTAGE OF METHOD:

°SIMPLE AND LESS EXPENSIVE TO USE IN FULL-SCALE PRAS

°CAN BE USED IN CONJUNCTION WITH MORE DETAILED CCFA COMPUTER CODES (SUCH AS MOBABE) WHEN FURTHER DETAIL IS REQUIRED IN THE PRA

°PROVIDES UTILITY ANALYST WITH SYSTEMATIC WAY TO INCORPORATE EXPERT OPINION AND BETTER WAY TO VALIDATE RESULTS OF THE ANALYSIS

°THE CAUSE TABLE APPROACH HAS BEEN EXTENSIVELY APPLIED AND THEREFORE REPRESENTS A BONAFIDE METHOD WHICH CAN BE EXTENDED FOR CCFA

SUGGESTED SCHEDULE FOR NEW PROJECT PROPOSAL:

"CCFA METHODS FOR LARGE-SCALE UTILITY PRAS"

(1) WRITE PRE-PROPOSAL OUTLINING IN GREATER DETAIL THE STUDY METHODOLOGICAL APPROACH (CAUSE TABLE & DPD)

(2) SUBMIT BY APRIL 1, 1982 FOR REVIEW BY UTILITY SPONSORS WITH PROJECTED DATE OF START-UP OF PROJECT AUGUST-SEPTEMBER, 1982.

(3) EXPECTED LEVEL OF SUPPORT REQUIRED: APPROXIMATELY 60K FOR 1 YEAR

(4) EXPECTED TIME FRAME: 1 YEAR (COMPLETED BY SEPTEMBER 1983)

(5) PROJECT STRUCTURE: MAINTAIN CURRENT STRUCTURE. FIND NEW STUDENT TO PURSUE WORK, PROBABLY AT SM LEVEL.

SUGGESTED SCHEDULE FOR NEW PROJECT PROPOSAL:

"CCFA METHODS FOR LARGE-SCALE UTILITY PRAS"

(1) WRITE PRE-PROPOSAL OUTLINING IN GREATER DETAIL THE STUDY METHODOLOGICAL APPROACH (CAUSE TABLE & DPD)

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SUGGESTED SCHEDULE FOR NEW PROJECT PROPOSAL:

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(4) EXPECTED TIME FRAME: 1 YEAR (COMPLETED BY SEPTEMBER 1983)

(5) PROJECT STRUCTURE: MAINTAIN CURRENT STRUCTURE. FIND NEW STUDENT TO PURSUE WORK, PROBABLY AT SM LEVEL.

F.2.2 Progress Review Meeting, August 30, 1982

PROFESSOR CAROLYN D. HEISING
NUCLEAR ENGINEERING DEPARTMENT
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

August 30, 1982

Dear Project Sponsor:

Today, we are reviewing the final work accomplished in the research project "Common Cause Analysis: A Review and Extension of Existing Methods". The major output of this project, which has involved a one-year funded research effort (10/1/81--9/30/82), has been the development of new computer code that can evaluate system fault trees quantitatively for common cause failures. The code, entitled MOBB for Mocus Bacfire Beta factor, has combined the generic cause approach of Fussel in the Bacfire-II package for the qualitative identification of common cause cutset candidates, with the Beta-Factor methods of Fleming and Raabe for their quantification. This code has also been developed with an uncertainty analysis propagation package based on two methods: (1) Monte Carlo simulation, and (2) heuristic analytic approach (Bier). The code has been applied to assess the ADS system at the Millstone nuclear power station, as well as to other example problems.

We plan to cover the work accomplished by myself and Mr. Cho Mak, who has recently completed his Engineer's thesis as a result of this project. A technical paper will be written and submitted to the journal Reliability Engineering by October 30, 1982. A user's manuel for the code has also been produced. This manual replaces that reported on in reference (2) below.

(1) Mak, C., "Assessment and Comparison of Qualitative Common Cause Failure Analysis Codes", S.M. Thesis, Nuclear Engineering Department, M.I.T., August, 1981.

(2) Heising, C.D., Karimi, R., Mak, C., Modarres, M., Rasmussen, N.C., and Wolf, L., User's Manual for MOCUS-BACFIRE: A Computer Program for Common Cause Failure Analysis, MIT-EL-81-037, Electric Utility Program, November 1981.

(3) Mak, C., Heising, C., and Modarres, M., "Application and Extension of the MOCUS-BACFIRE Common Cause Analysis Code to Reactor Safety Systems", Session IV-B, Common Mode Failures, International ANS/ENS Topical Meeting on Probabilistic Risk Assessment, Port Chester, New York, September 20-24, 1981.

We will be mailing to you in the next two weeks the completed Engineer's thesis and the user's manual. We will also send to you copies of the technical paper when completed.

Additionally, we hope you will consider funding the follow-up project as proposed (see attachment).

Sincerely,

Carolyn D. Heising

Carolyn D. Heising

CDH/sc

-M.I.T. COMMON CAUSE ANALYSIS PROJECT-

PROJECT OVERVIEW AND STATUS REPORT

- Final -

PROFESSOR C. HEISING

NUCLEAR ENGINEERING DEPARTMENT

AUGUST 30, 1982

REVIEW OF PROJECT TASKS

TASK 1: ASSESSMENT OF EXISTING QUALITATIVE COMMON CAUSE FAILURE ANALYSIS CODES THAT USE GENERIC CAUSE APPROACH TO IDENTIFY COMMON CAUSE CANDIDATES FROM MINIMAL CUT SETS

-COMCAN VERSIONS

-BACFIRE VERSIONS

-SETS (SANDIA)

STATUS: COMPLETED APRIL 1981

CONCLUSION: BACFIRE IS PREFERABLE OVER THE OTHERS, AND IS THE CODE SELECTED FOR INTEGRATION WITH QUANTITATIVE EVALUATION METHODS

TASK 2: CHOOSE AN APPROPRIATE QUANTITATIVE METHOD TO QUANTIFY THE COMMON CAUSE CANDIDATES AND EVALUATE THE SYSTEM UNAVAILABILTY

STATUS: COMPLETED MAY 1981

CONCLUSIONS: BETA-FACTOR METHOD DEVELOPED BY KARL FLEMING AT GENERAL ATOMIC FOR HTGR-PRA IS PREFERABLE. THIS METHOD WAS INTEGRATED INTO THE MODIFIED BACFIRE PACKAGE. (IT HAS ALSO BEEN REFINED AND UPDATED).

PRODUCT: MOBABE CODE
(MOCUS - BACFIRE - BETA FACTOR METHOD)

TASK 3: IMPLEMENTATION OF THE QUALITATIVE METHOD CHOSEN TO QUANTIFY COMMON CAUSE CANDIDATES AND EVALUATE SYSTEM UNAVAILABILITY

STATUS: COMPLETED AUGUST 1981

CONCLUSIONS: SAMPLE PROBLEMS WERE RUN USING THE MOBABE CODE. THESE INCLUDED ANALYSES OF THE FOLLOWING TWO SYSTEMS:

- AUXILIARY FEEDWATER SYSTEM (AFWS)
- FIRE PROTECTION SYSTEM (FPS)

DOCUMENTATION:

- CHO MAK'S SM THESIS
- PAPER FOR PORTCHESTER PRA MEETING

PRODUCT: USEFUL EXAMPLES TO GUIDE UTILTY EFFORTS IN SYSTEMS ANALYSIS.

TASK 4: REVIEW AND FURTHER EXTEND THE CAPABILITIES OF THE CODE TO INCLUDE UNCERTAINTY ANALYSIS, DATA COLLECTION AND INTERPRETATION; RE-DEFINE PARAMETERS AND FAILURE CRITERION.

STATUS: COMPLETED

Additionally, a separate code for uncertainty analysis using the DPD method of seismic risk analysis (HADES code). Examples have been run

PRELIMINARY CONCLUSIONS:

- MONTE CARLO METHOD APPLICABLE
- HAS BEEN INCORPORATED INTO MOBS
- SAMPLE PROBLEMS RUN

FURTHER WORK NEEDED (BEYOND THIS PROJECT SCOPE):

- MORE EFFICIENT METHOD REQUIRED TO REDUCE COMP. TIME

TASK 5: USE OF FINAL VERSION OF THE CODE FOR A DETAILED COMMON CAUSE FAILURE ANALYSIS

STATUS:

COMPLETED

DATE OF COMPLETION:

END OF JUNE, 1982

FINAL PRODUCT: REVISED CODE ON TAPE FOR USE IN IBM-370 SYSTEM

DOCUMENTATION: UPDATED FINAL CODE USER'S MANUAL

CHO MAK'S ENGINEER'S THESIS

TECHNICAL PAPER TO BE SUBMITTED TO RELIABILITY ENGINEERING JOURNAL

-M.I.T. COMMON CAUSE ANALYSIS PROJECT-

APPLICATION OF STUDY RESULTS TO NPP RISK ASSESSMENTS: FUTURE PLAN

PROFESSOR C. HEISING

NUCLEAR ENGINEERING DEPARTMENT

AUGUST 30, 1982

°BENEFITS OF PRESENT WORK:

°EMPHASIS HAS BEEN ON CODE DEVELOPMENT PRIMARILY FOR UTILITY SYSTEMS RELIABILITY ANALYSIS

°ADVANTAGES:

CODE PROVIDES SYSTEMATIC FRAMEWORK FOR PERFORMING A DETAILED ANALYSIS OF SYSTEM AVAILABILITY (POINT ESTIMATE PLUS UNCERTAINTY BOUNDS)

°DISADVANTAGES:

USE OF SUCH DETAILED INFORMATION IN A PRA MAY NOT BE NECESSARY.

°A SIMPLIFIED APPROACH TO CCFA MAY BE MORE DESIRABLE IN A FULL-SCALL UTILITY PRA FOR REASONS OF REDUCED COST AND ENHANCED USE OF THE AVAILABLE DATA

- DIRECTIONS FOR FUTURE WORK:

  - FOCUS ON UTILITY PLANT-SPECIFIC PRA'S

    METHODS FOR CCFA WILL BE BROADER AND MORE SIMPLIFIED

- PROPOSED METHODOLOGICAL APPROACH

  CAUSE-TABLE APPROACH --(CAUSE TABLE - DPD)

  - THIS IS THE SIMPLIFIED FAULT TREE ANALYSIS METHOD USED IN THE Z/IP STUDIES

  - BENEFIT TO UTILITY IS REDUCED COST AND MORE MANAGEABLE FAULT TREES

  - CAUSE TABLE REQUIRES FULL DETAILED UNDERSTANDING OF SYSTEM, MUST INCORPORATE EXPERT JUDGEMENT INTO NUMERICAL EVALUATIONS

TABLE 3-1. EXAMPLE CAUSE TABLE FOR CAUSES AFFECTING SINGLE AND MULTIPLE COMPONENTS

SYSTEM: Sample
COMPONENTS: A, B, C, D, E, F, G
MINIMAL CUTSETS: A, D, BC, EFG

Part I - Accident Sequence Dependent Boundary Conditions			
Initiating Event	Accident Sequence	Interfacing Systems Failures and Boundary Conditions	Changes in Internal and External Environment

Part II - Single Failure Cause Sets							
Cause Category	Components						
	A	B	C	D	E	F	G
Hardware Environmental Test Maintenance Operator Error Other							

Part III - Multiple Failure Cause Sets					
Cause Category	Component Failure Sets				
	BC	EF	FG	EG	EFG
Human Interactions Design Error Manufacturer/ Installation Error Operator Error Test/Maintenance Error Physical Interactions Excessive Temperature Excessive Pressure Excessive Vibration Excessive Impact Corrosive Agent Excessive Moisture Other					

TABLE 3-2. DEPENDENT FAILURES ASSOCIATED WITH A CAUSE TABLE TYPE OF SYSTEMS ANALYSIS

I. Accident Sequence Dependent Boundary Conditions
A. Failures of Interfacing/Support Systems (shared equipment dependencies in Table 1-2) B. Sequence Dependent Environmental Changes C. Sequence Dependent Exceedance of System Operating Limits D. Other
II. Common Cause Failures
A. Human Interactions 1. Design Error 2. Manufacturing/Installation Errors 3. Operator Errors 4. Test/Maintenance Errors B. Physical Interactions (excessive environmental stresses) C. Other
III. Multiple Failures Resulting from Different but Dependent Causes
A. Propagating Failures B. Technical Specification Dependencies C. Other

- DPD METHOD FOR EXTERNAL EVENT ANALYSIS:

  - REFINE DPD METHOD USED FOR EXTERNAL EVENT ANALYSIS TO EXTEND TO OTHER TYPES OF COMMON CAUSE EVENTS (E.G.; HUMAN ERROR, ENVIRONMENTAL FACTORS: CORROSION, DEGRADATION, ETC.)

ADVANTAGE OF METHOD:

- SIMPLE AND LESS EXPENSIVE TO USE IN FULL-SCALE PRAS

- CAN BE USED IN CONJUNCTION WITH MORE DETAILED CCFA COMPUTER CODES (SUCH AS MOBABE) WHEN FURTHER DETAIL IS REQUIRED IN THE PRA

- PROVIDES UTILITY ANALYST WITH SYSTEMATIC WAY TO INCORPORATE EXPERT OPINION AND BETTER WAY TO VALIDATE RESULTS OF THE ANALYSIS

- THE CAUSE TABLE APPROACH HAS BEEN EXTENSIVELY APPLIED AND THEREFORE REPRESENTS A BONAFIDE METHOD WHICH CAN BE EXTENDED FOR CCFA

Research Proposal

COMMON CAUSE ANALYSIS METHODS FOR LARGE SCALE UTILITY PRAs

Principal Investigator: Prof. Carolyn Heising
(617) 253-5119

Submitted by:

Energy Laboratory
and
Department of Nuclear Engineering

Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

July 1982

A LIST OF POTENTIAL COMMON CAUSES:

EXTERNAL EVENTS - SEIMIC EVENTS

FIRE

FLOOD

EXTREME WEATHER

.

.

.

.

INTERNAL EVENTS - ENGINEERING DESIGN ERRORS

TESTING & MAINTENANCE

EXTREME OPERATING ENVIRONMENT

OPERATOR ERRORS

.

.

.

.

UNCERTAINTY ANALYSIS

MONTE CARLO METHOD -

USE SIMULATIONS TO OBTAIN TOP EVENT FAILURE PROBABILITY DISTRIBUTION BY SPECIFY BASIC EVENTS' DISTRIBUTION.

METHOD OF MOMENTS -

CALCULATE TOP EVENT DISTRIBUTION MOMENTS BY PROPAGATING UNCERTAINTIES FROM THE BASIC EVENTS LEVEL TO CUT SETS' LEVEL AND THEN TO SYSTEM LEVEL.

ASSUMPTIONS:

VARIATES ARE LOGNORMALLY DISTRIBUTED,

FAILURE PROBABILITIES $\ll .01$

SYSTEM FAILURE PROBABILITY $< .01$

Log-normal Distribution S_l

$$S_l(x,\mu,\sigma) = \frac{1}{x\,\sigma\sqrt{2\pi}} \exp[(\ln(x)-\mu)^2/(-2\sigma^2)] \qquad 0 < x < \infty$$

$$= 0 \qquad 0 \leq x$$

$$\text{mth moment} = \exp[m\,\mu + \frac{m^2\sigma^2}{2}]$$

Bounded Log-normal Distribution S_b

$$S_b(x,\mu,\sigma) = \frac{1}{x(1-x)\sigma\sqrt{2\pi}} \exp[(\ln(\frac{x}{1-x}) - \mu)^2/(-2\sigma^2)] \qquad 0 < x < 1$$

$$= 0 \qquad \text{otherwise}$$

$$\text{mth moment} = \int_0^1 x^m\, S_b(x,\mu,\sigma)\, dx$$

Truncated Log-normal Distribution S_t

$$S_t(x,\mu,\sigma) = \frac{c}{x\,\sigma\sqrt{2\pi}} \exp[(\ln(x)-\mu)^2/(-2\sigma^2)] \qquad 0 < x < 1$$

$$= 0 \qquad \text{otherwise}$$

$$\text{mth moment} = \int_0^1 x^m\, S_t(x,\mu,\sigma)\, dx$$

where c is the normalization factor

$$c = \int_0^1 S_l(x,\mu,\sigma)\, dx$$

The variance of F is the second moment about the mean:

$$\mathrm{var}(F) = E[F^2] - (E[F])^2$$

$$= \sum_{i=1}^{n} \left(\frac{\delta f}{\delta X_i}\right)^2 \mathrm{var}(X_i) + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{\delta^2 f}{\delta X_i \delta X_j} \mathrm{cov}(X_i, X_j) + \cdots \quad \text{(A7)}$$

When fault tree method is used for analyzing system failure probability the system equation is often expressed in sum of product form. Two special cases where F is either the sum or the product of its component distributions.

<u>Case 1</u>

$$F = f(X_1, X_2, \ldots X_n)$$

$$= \sum_{i=1}^{n} X_i \quad \text{(A8)}$$

<u>Mean</u>

$$E[F] = \sum_{i=1}^{n} \bar{X}_i \quad \text{(A9)}$$

<u>Variance</u>

$$\mathrm{var}(F) = \sum_{i=1}^{n} \mathrm{var}(X_i) + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{cov}(X_i, X_j) \quad \text{(A10)}$$

<u>Case 2</u>

$$F = f(X_1, X_2, \ldots X_n)$$

$$= \prod_{i=1}^{n} X_i \quad \text{(A11)}$$

Mean

$$E[F] = \prod_{i=1}^{n} \bar{X}_i + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{\hat{X}}{\bar{X}_i \bar{X}_j} \operatorname{cov}(X_i, X_j) \tag{A12}$$

Variance

$$\begin{aligned} \operatorname{var}(F) = & \sum_{i=1}^{n} \left[\frac{\hat{X}}{\bar{X}_i} \right]^2 \operatorname{var}(X_i) \\ & + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \left[\frac{\hat{X}}{\bar{X}_i \bar{X}_j} \right]^2 E[(X_i - \bar{X}_i)^2 (X_j - \bar{X}_j)^2] \\ & + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{\hat{X}^2}{\bar{X}_i \bar{X}_j} \operatorname{cov}(X_i, X_j) \end{aligned} \tag{A13}$$

where $\hat{X} = \prod_{k=1}^{n} \bar{X}_k$

Log-normal Distribution S_l

$$S_l(x,\mu,\sigma) = \frac{1}{x\,\sigma\sqrt{2\pi}} \exp[(\ln(x)-\mu)^2/(-2\sigma^2)] \qquad 0 < x < \infty$$

$$= 0 \qquad 0 \leq x$$

$$\text{mth moment} = \exp[m\,\mu + \frac{m^2}{2}\sigma^2]$$

Bounded Log-normal Distribution S_b

$$S_b(x,\mu,\sigma) = \frac{1}{x(1-x)\sigma\sqrt{2\pi}} \exp[(\ln(\frac{x}{1-x}) - \mu)^2/(-2\sigma^2)] \qquad 0 < x < 1$$

$$= 0 \qquad \text{otherwise}$$

$$\text{mth moment} = \int_0^1 x^m\, S_b(x,\mu,\sigma)\, dx$$

Truncated Log-normal Distribution S_t

$$S_t(x,\mu,\sigma) = \frac{c}{x\,\sigma\sqrt{2\pi}} \exp[(\ln(x)-\mu)^2/(-2\sigma^2)] \qquad 0 < x < 1$$

$$= 0 \qquad \text{otherwise}$$

$$\text{mth moment} = \int_0^1 x^m\, S_t(x,\mu,\sigma)\, dx$$

where c is the normalization factor

$$c = \int_0^1 S_l(x,\mu,\sigma)\, dx$$

S_b

Median	ef	M1	M2	Variance
$1x10^{-2}$	3	$1.25x10^{-2}$	$2.42x10^{-4}$	$8.64x10^{-5}$
$1x10^{-2}$	10	$2.52x10^{-2}$	$2.75x10^{-3}$	$2.12x10^{-3}$
$3x10^{-2}$	3	$3.73x10^{-2}$	$2.15x10^{-3}$	$7.55x10^{-4}$
$3x10^{-2}$	10	$7.25x10^{-2}$	$1.75x10^{-2}$	$1.22x10^{-2}$
$1x10^{-3}$	3	$1.25x10^{-3}$	$2.44x10^{-6}$	$8.78x10^{-7}$
$1x10^{-3}$	10	$2.64x10^{-3}$	$4.34x10^{-5}$	$3.65x10^{-5}$
$3x10^{-3}$	3	$3.75x10^{-3}$	$2.19x10^{-5}$	$7.87x10^{-6}$
$3x10^{-3}$	10	$7.81x10^{-3}$	$3.32x10^{-4}$	$2.71x10^{-4}$

S_t

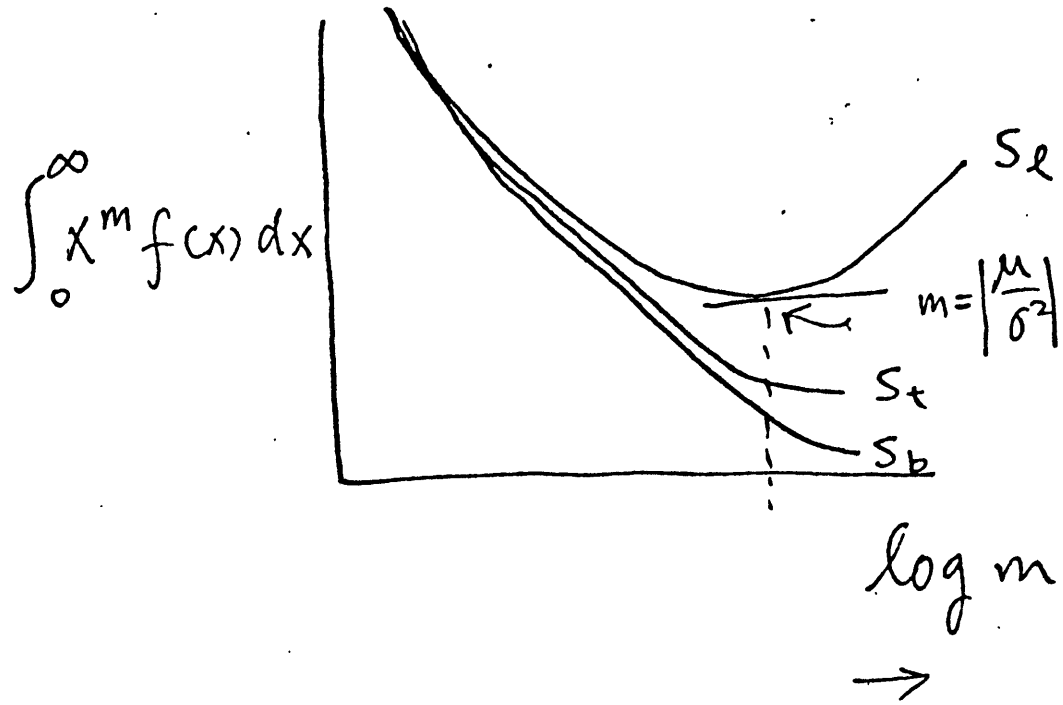
Median	ef	M1	M2	Variance
$1x10^{-2}$	3	$1.25x10^{-2}$	$2.44x10^{-4}$	$8.78x10^{-5}$
$1x10^{-2}$	10	$2.59x10^{-2}$	$3.47x10^{-3}$	$2.80x10^{-3}$
$3x10^{-2}$	3	$3.75x10^{-2}$	$2.20x10^{-3}$	$7.90x10^{-4}$
$3x10^{-2}$	10	$6.96x10^{-2}$	$1.75x10^{-2}$	$1.27x10^{-2}$
$1x10^{-3}$	3	$1.25x10^{-3}$	$2.44x10^{-6}$	$8.78x10^{-7}$
$1x10^{-3}$	10	$2.66x10^{-3}$	$4.95x10^{-5}$	$4.24x10^{-5}$
$3x10^{-3}$	3	$3.75x10^{-3}$	$2.20x10^{-5}$	$7.90x10^{-6}$
$3x10^{-3}$	10	$7.97x10^{-3}$	$4.12x10^{-4}$	$3.49x10^{-4}$

Boolean Expression for system unavailability:

$S = X_1 + X_2X_3 + X_4X_5 + X_6$

Basic Events	Median of failure probabilities
X_1	$1x10^{-3}$
X_2	$3x10^{-2}$
X_3	$1x10^{-2}$
X_4	$3x10^{-2}$
X_5	$1x10^{-2}$
X_6	$3x10^{-3}$

	RF=3		RF=10	
Method	Mean	Variance	Mean	Variance
Discrete	$5.936x10^{-3}$	$7.2x10^{-6}$	$1.49x10^{-2}$	$2.14x10^{-4}$
Method of Moments: S_1	$5.936x10^{-3}$	$9.4x10^{-6}$	$1.491x10^{-2}$	$8.76x10^{-4}$
S_b	$5.933x10^{-3}$	$9.4x10^{-6}$	$1.410x10^{-2}$	$3.97x10^{-4}$
S_t	$5.938x10^{-3}$	$9.4x10^{-6}$	$1.424x10^{-2}$	$4.80x10^{-4}$
Monte Carlo Sample (3000)	$5.955x10^{-3}$	$8.6x10^{-6}$	$1.426x10^{-2}$	$3.97x10^{-4}$
Sample (1200)	$5.996x10^{-3}$	$9.3x10^{-6}$	$1.477x10^{-2}$	$4.73x10^{-4}$
Discrete (1200)	$5.788x10^{-3}$	$6.3x10^{-6}$	$1.402x10^{-2}$	$1.89x10^{-4}$



m moment

$S_\ell \sim S_t$ $\qquad m \leq n \left|\frac{\mu}{\sigma^2}\right|$

$n \simeq 2.0$

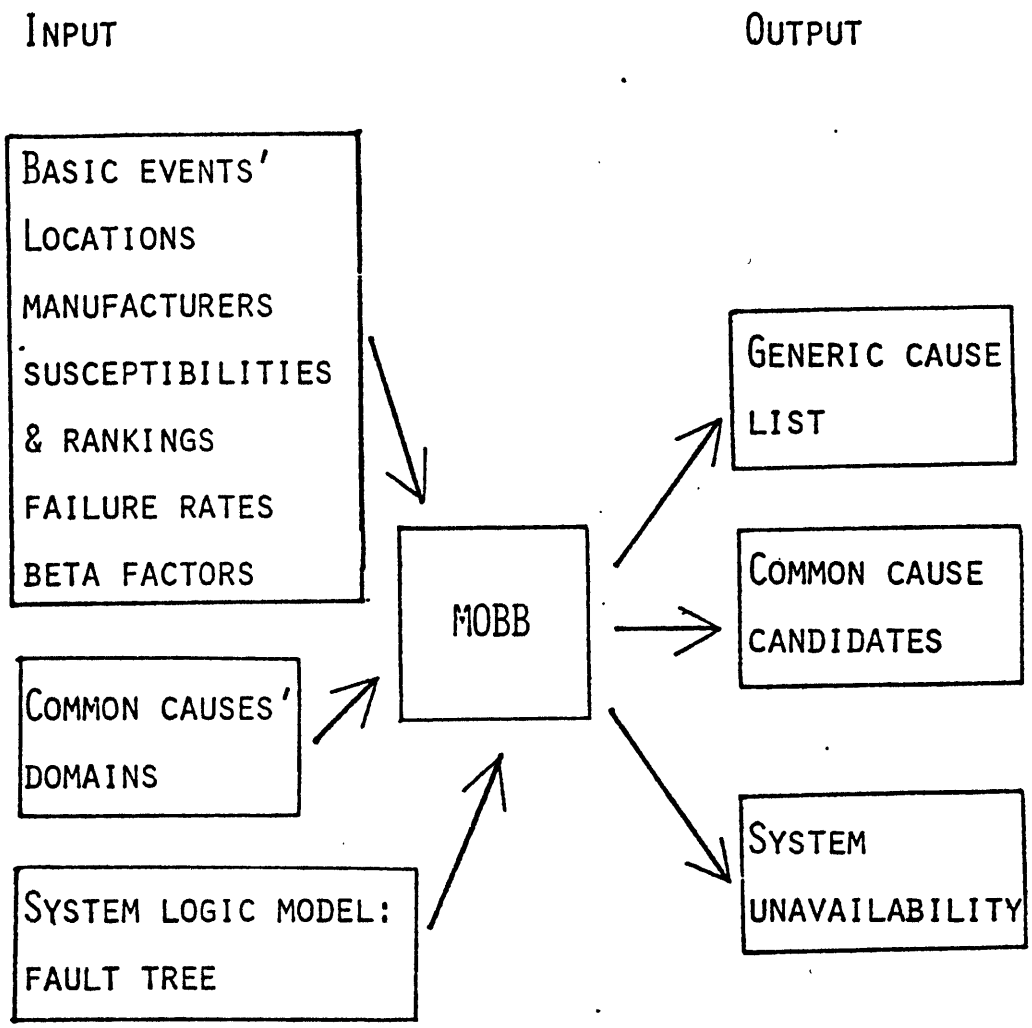
m moment

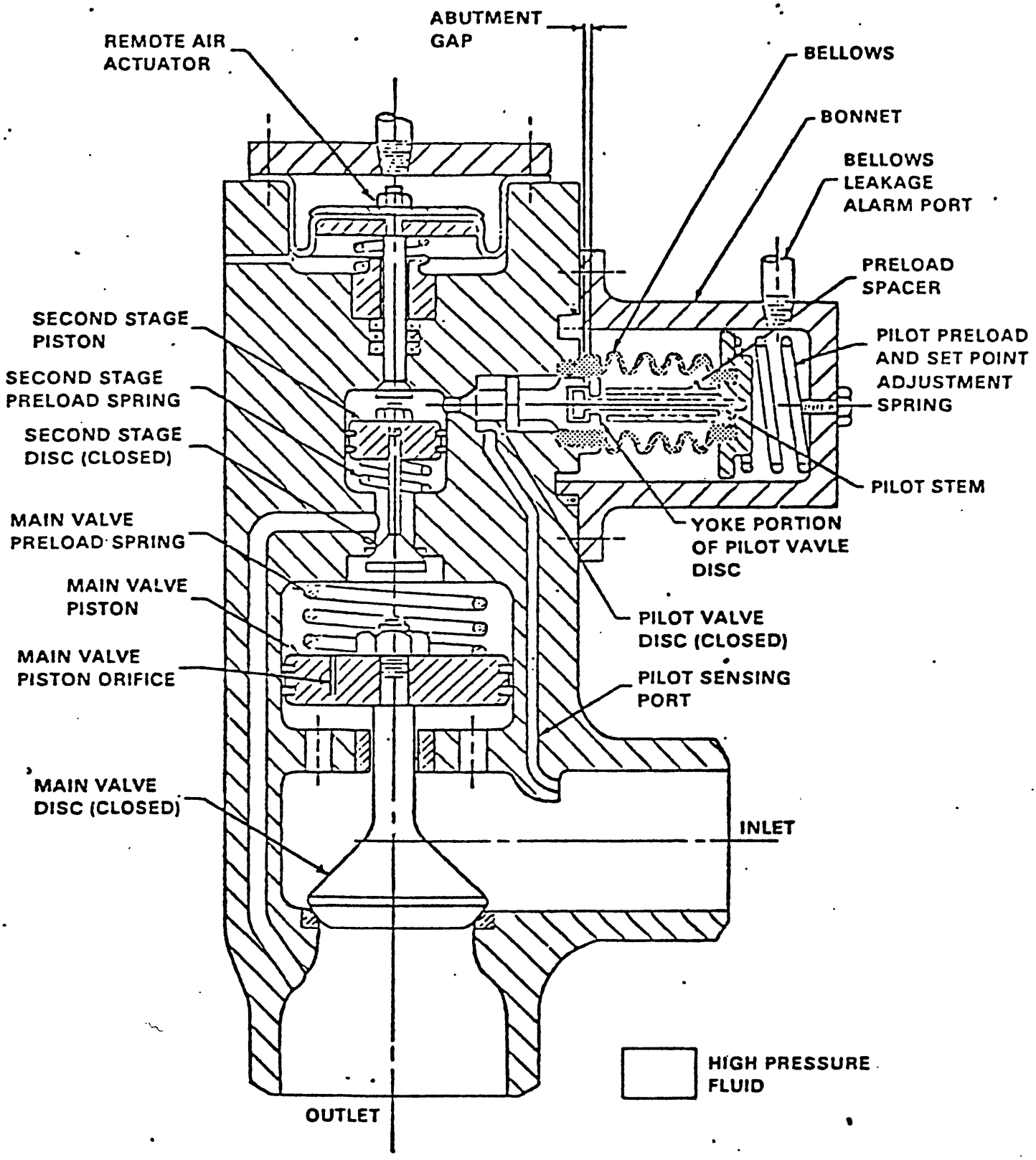
$S_b \sim S_\ell$ $\qquad m \leq n \left|\frac{\mu}{\sigma^2}\right|$

$n \simeq 6.0$

W. E. Coyote

Rule

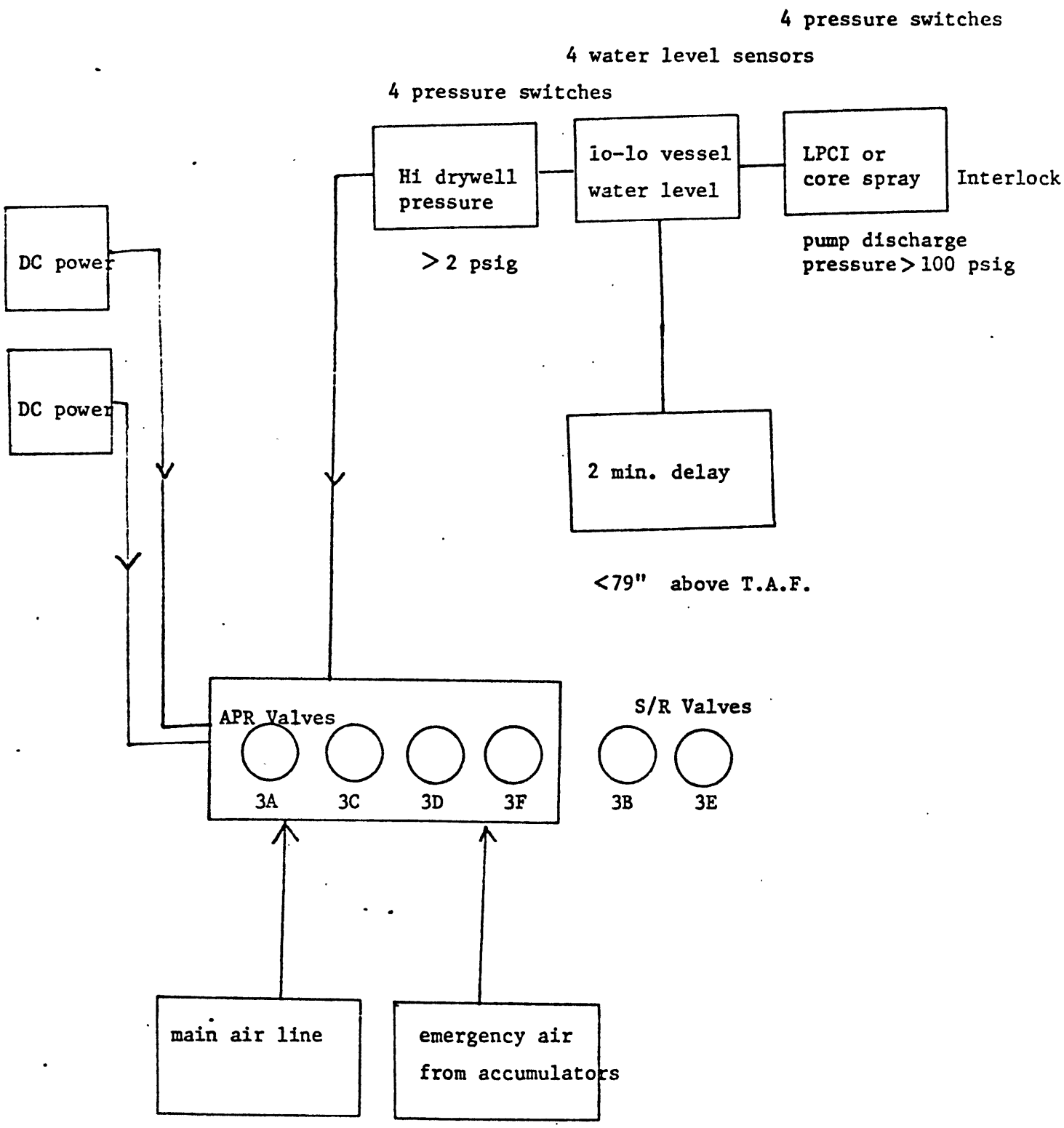

INPUT
OUTPUT
BASIC EVENTS' LOCATIONS MANUFACTURERS SUSCEPTIBILITIES & RANKINGS FAILURE RATES BETA FACTORS
COMMON CAUSES' DOMAINS
SYSTEM LOGIC MODEL: FAULT TREE
MOBB
GENERIC CAUSE LIST
COMMON CAUSE CANDIDATES
SYSTEM UNAVAILABILITY



APR VALVE SCHEMATIC (CLOSED)

Valves	Set Point	Location(main Steam Lines)
APR-3A	1095 psig	A
APR-3D	1110 psig	B
APR-3C	1125 psig	C
APR-3F	1125 psig	D
S/R-3B	1125 psig	B
S/R-3E	1125 psig	C

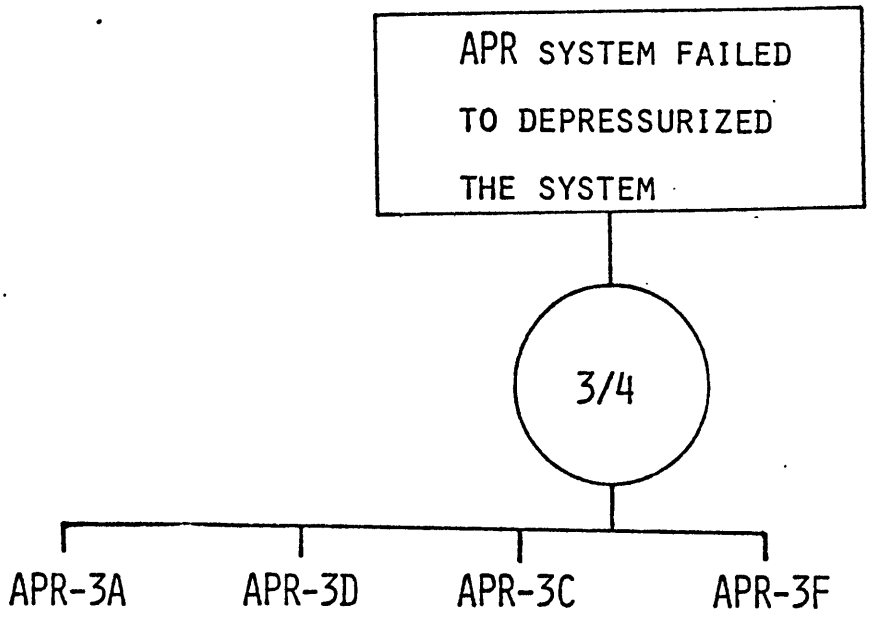
AUTO-REMOTE ACTUATION OF APR VALVE



1) BLOWDOWN FOR LPCI SYSTEMS

SMALL LOCA

SUCCESS CRITERIA: 2 OUT OF 4 AUTO/REMOTE MODE



2) RELIEF/SAFETY VALVES ACTUATION

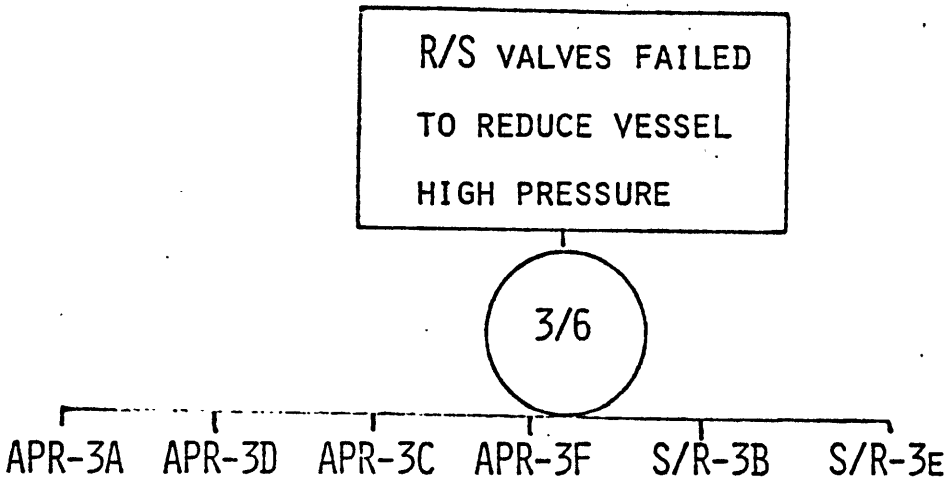
TO RELIEF HIGH VESSEL PRESSURE

FULL POWER PRESSURE 1000 PSIG

DESIGN LIMIT 1375 PSIG

SUCCESS: ANY 4 OUT OF 6 APR OR R/S VALVES

- TURBINE TRIP FROM FULL POWER
- A FAILURE OF THE TURBINE BYPASS SYSTEM
- A FAILURE OF THE DIRECT REACTOR SCRAM BASED ON STOP VALVE POSITION

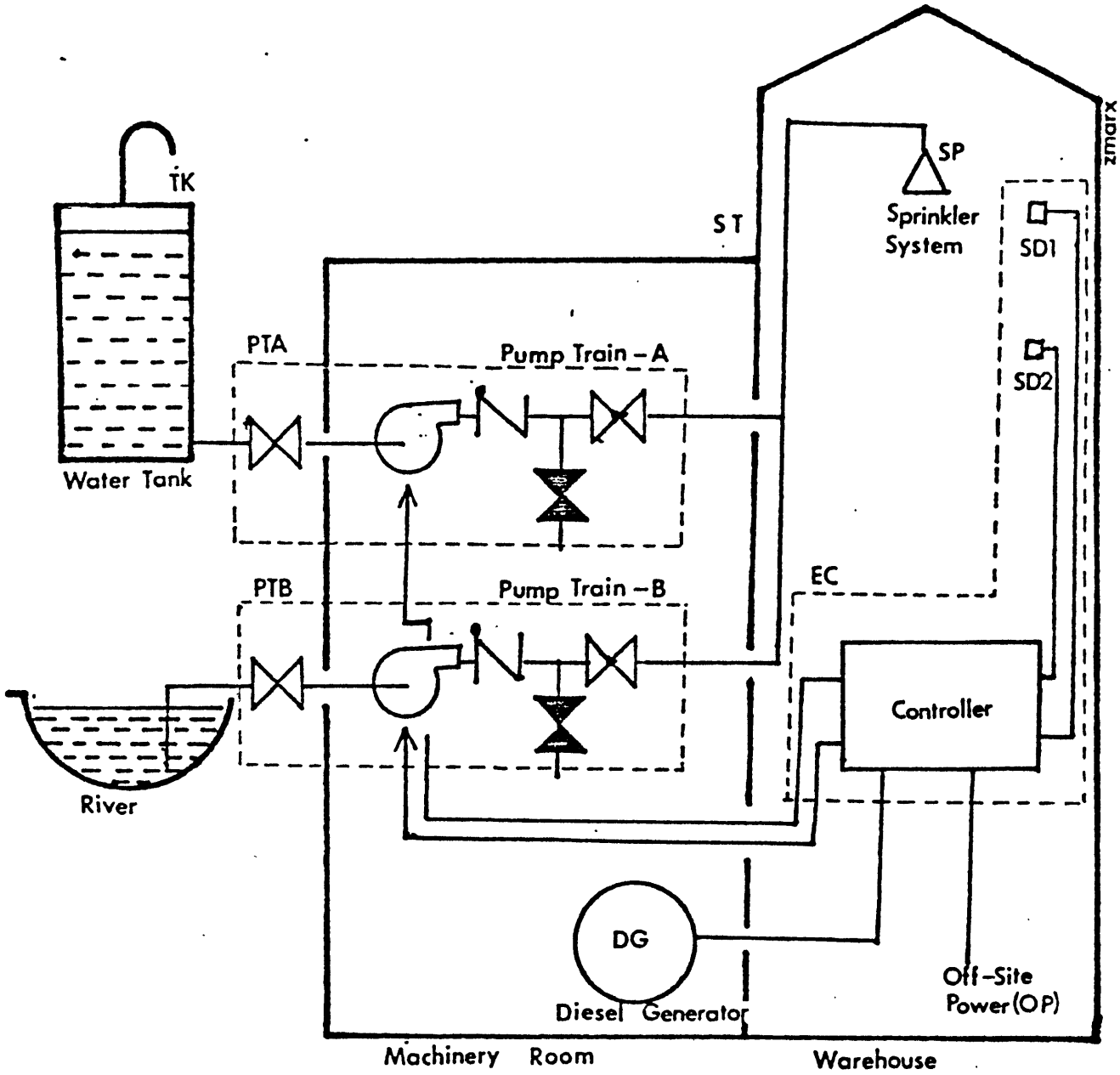


3) MANUAL ACTUATION MODE

ALL SIX VALVES CAN BE REMOTELY OPENED FROM THE COMTROL ROOM.

FOR PRESSURE RELIEF	4/6
FOR BLOWDOWN	2/4

HUMAN ERRORS IS THE MAJOR CONTRIBUTOR



WAREHOUSE SAMPLE PROBLEM SCHEMATIC DIAGRAM

Boolean Expression

$F = ST + SP + T_A + T_B$

where $T_A = PT_A + TK + (EC + OP * DG)$

$T_B = PT_B + (EC + OP * DG)$

$F = ST + SP + PT_A * PT_B + EC + OP * DG + TK * PT_B$

F : System failure due to seismic events

The following events are conditional to the seismic events:

ST : Structure (building and supporting structure for components to attach on)

SP : Sprinkling System

T_A : Pump Train A

T_B : Pump Train B.

PT_A: Pump A and associated valves and piping

PT_B: Pump B and associated valves and piping

TK : Water Storage Tank

OP : Off-Site Power Supplies

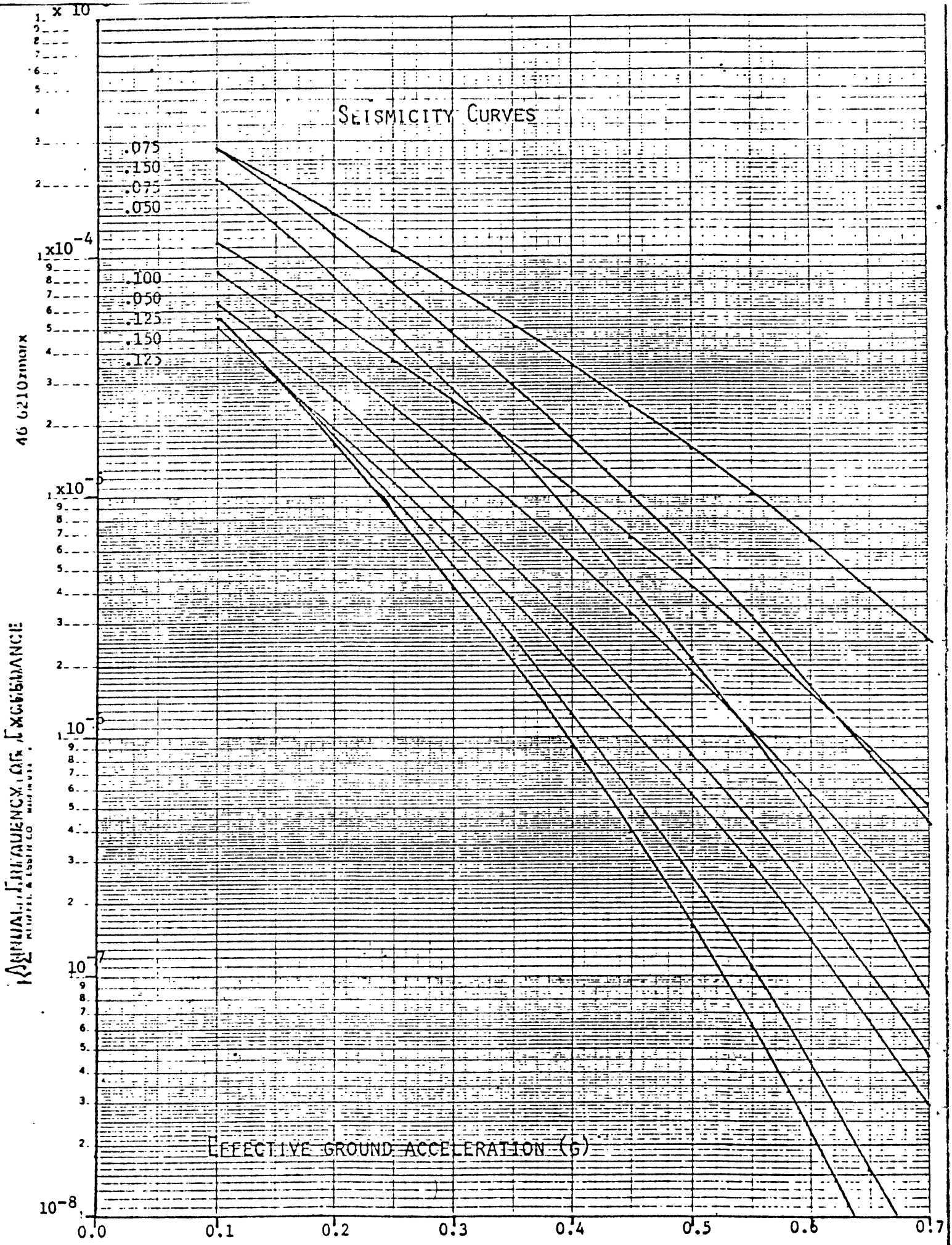
DG : Diesel Generator

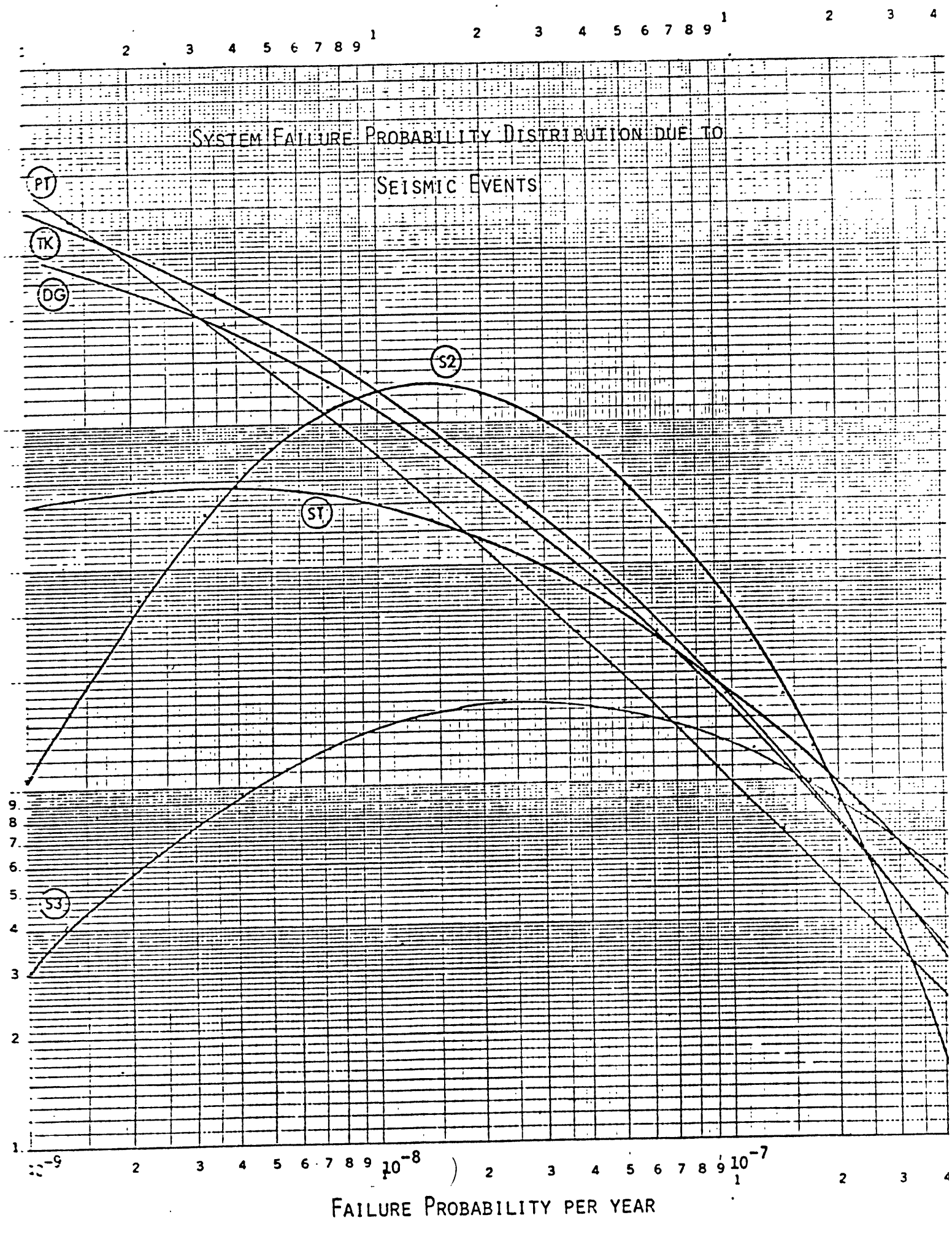
EC : Electronic Detection and Control System

Common External Initiating Events

(Ref: PRA Procedure Guide NUREG/CR-2300, Chapter 11)

- Develop hazard model for the initiating events
- frequency of exceedance vs intensity curves
- Develop response model
- Components' or subsystems' fragility curves
- Convolving the frequency with the fragility functions
- Develop system logic model (fault tree - event tree)
- System failure probability distribution
  (for nuclear plant risk assessment)
  - Plant state
  - Release categories
  - Consequence models
  - Risk curves


SEISMICITY CURVES
.075
.150
.075
.050
.100
.050
.125
.150
.125
ANNUAL FREQUENCY OF EXCEEDANCE
EFFECTIVE GROUND ACCELERATION (G)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7


SYSTEM FAILURE PROBABILITY DISTRIBUTION DUE TO
SEISMIC EVENTS
PT
TK
DG
S2
ST
S3
FAILURE PROBABILITY PER YEAR

SAMPLE PROBLEM

METHOD 1: -ESTABLISHED SEISMIC FREQUENCY CURVES

-SPECIFIED COMPONENTS' FRAGILITY FUNCTIONS

-COMPUTE COMPONENTS' FAILURE PROBABILITY DISTRIBUTION FUNCTIONS (DPD)

-COMPUTE SYSTEM FAILURE PROBABILITY DISTRIBUTION USING THE DPD METHOD

MEAN = 1.52×10^{-7}/YR

VAR = 2.09×10^{-14}

MEAN TO STANDARD DEVIATION RATIO = 1.0514

METHOD 2: -SIESMICITY CURVES

-COMPONENTS' FRAGILITY FUNCTIONS

-USE THE METHOD OF MOMENTS TO FIND THE SYSTEM FRAGILITY FUNCTIONS

-COMPUTE SYSTEM UNAVAILIABILITY DISTRIBUTION FUNCTION (DPD)

MEAN = 7.14×10^{-8}/YR

VAR = 5.09×10^{-15}

MEAN TO STANDARD DEVIATION RATIO = 1.0008

F.3 Original Proposal of July, 1981

Original Proposal

Research Proposal

on

COMMON CAUSE ANALYSIS: A REVIEW AND EXTENSION OF EXISTING METHODS

10/1/81--9/30/82

Carolyn Heising-Goodman
Principal Investigator
Nuclear Engineering Department
Carolyn Heising-Goodman

Norman C Rasmussen
Co-Investigator
Nuclear Engineering Department
Norman C. Rasmussen

Energy Laboratory
and
Department of Nuclear Engineering
Massachusetts Institute of Technology

July 1981

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1. Objectives of The Proposal

The main objective of the proposed research is to further assess and extend the MOCUS-BACFIRE Package Code (1), COMCAN-II code (2) and BACFIRE-II Code (3) to provide the utilities with an effective and powerful tool for analysis and evaluation of common cause failures (CCF) in a system represented by its fault tree diagram. Based on the existing version of these three codes it is suggested that the research be focused on the following areas:

(1) Assessment and comparison of MOCUS-BACFIRE, COMCAN-II, and BACFIRE-II codes,

(2) Redefinition of existing criteria for identifying CCFs and incorporating them into the selected code.

(3) Selection and incorporation of a more sophisticated common cause quantification technique into the selected code.

(4) With close cooperation of the utilities, a problem of their interest will be evaluated using the improved version.

A detailed review of each of the above will follow in Section 4.

2. Expected Benefits

The expected benefits for the utilities are to obtain a code which is:

(1) capable of identifying common cause failures directly from the fault tree diagram;

(2) inexpensive and easy to operate;

(3) capable of automatically generating common cause candidates which are significantly contributing to the failure of the system due to common cause failures;

(4) capable of calculating the top event probability (or unavailability) by considering both random and common cause failures;

(5) especially suited for man-machine communication and its advantages.

It should be noted that previous experiences in the field of common cause failure analysis at MIT (1) have emphasized the importance of these benefits in a complete system safety and risk analysis. These features would constitute a capability for the sponsoring utilities which is otherwise only available by using several different codes.

3. Short Review of State-of-the-Art

Unavailability calculations of engineering safety features and risk assessment studies (4,5) revealed the importance of considering potential common cause failures in estimating the probability of failure of redundant systems. It is a well-recognized fact that reliability predictions of redundant systems are overestimated when the potential for common cause failures is not properly accounted for. In fact, the RSS amply demonstrated that CCF may contribute the most to system unavailability.

The state-of-the-art of CCF analysis up to 1979 has been reviewed by Rasmussen et al. (6). Hayden (7) separated CCF's

into component and system failures and categorized them in terms of generic failure mechanisms such as design error, human error and energetic events. Apostolakis (8) used a constant hazard rate for reliability and redefined the hazard rate by using a point estimate of the conditional probability that a unit failure is due to a common cause failure.

Certainly the most thorough CCF analysis was performed as part of the RSS in each of the following analysis steps:

- Event tree construction
- Fault tree construction
- Fault tree quantification
- Event tree quantification
- Special engineering investigations

Computerized efforts in the qualitative and quantitative procedure of common cause failures were begun with special emphasis after the publication of the RSS. Burdick et al. (9) reported on COMCAN Code. This code is designed to aid in the qualitative determination of:

1) single secondary events that could fail entire minimum cutset, given all components in the cutset share the same susceptibility location.
2) Common links among components such as common circuitry, common maintenance personnel or common manufacturers for all components in a cutset.

As a result, COMCAN requires as one of its inputs, a set of minimal cutsets which have been obtained by some other qualitative analysis code. It is quite apparent that for large fault trees

with a high degree of replications and the possibility of several common cause failures, the computational efforts involved in the minimal cutset sorting become tremendous, if not impossible, due to the large amount of minimal cutsets. Modarres et al. (1) have developed a computer code package to resolve this difficulty by coupling the cutset generator code MOCUS (10) and common cause failure analysis code BACFIRE (11) to obtain the MOCUS-BACKFIRE Package. The BACFIRE Code is a newer and more adequate version of the COMCAN Code. However, a newly developed version of the COMCAN Code, which is called COMCAN-II (2), has been recently developed to directly evaluate common cause failures from the fault tree diagram. Similarly, BACFIRE is extended to obtain BACFIRE-II Code (3). Therefore, codes COMCAN-II, BACFIRE-II and MOCUS-BACFIRE have relatively similar capabilities. However, they employ different algorithms to determine CCFs, and the efficiency and limitations of these codes are not compared and assessed yet. The development of the COMCAN methodology laid the ground for the first time with basic rules which will be common to all future efforts involving common cause handling. The most important thing which was realized during the course of the development of this code is the recognition of the importance of generic classification. The possible physical sources for a specific secondary event can develop into an absolutely endless list. Only a unique generic classification makes the search for minimal cutsets sharing susceptibilities a tractable task. For this purpose, a preprocessor has been implemented in COMCAN which needs as input generic categorization of secondary causes.

A special category has been added which links conditions among components to locate potential common cause failures of minimal cutsets. The other three categories considered by COMCAN are:

- Mechanical or Thermal
- Electrical or Radiation
- Chemical or Miscellaneous

Recent studies (1, 12) have shown that the criteria for identifying a cutset as a common cause candidate in COMCAN code is not unique and sufficient for a complete CCF analysis. It is important, however, to select an adequate set of CCF criteria in order to obtain a set of adequate common cause candidates.

The review of computerized qualitative common cause failure analysis suggests the following conclusions. First, the original COMCAN code's approach, which uses the complete minimal cutset information, has no potential for further development because of a prohibitive amount of cutsets that must be input to the code for a large fault tree. Second, the codesMOCUS-BACFIRE, COMCAN-II and BACFIRE-II are the only codes that are recently developed to eliminate the necessity to input the cutsets. Therefore, instead of the cutsets, they require the fault tree to be input. However, they are not fully tested and assessed. A careful revision is required to establish a set of new criteria for identification of common cause candidates from the cutsets.

The state-of-the-art in common cause quantification is largely determined by the work described in WASH-1400 and the new developments by Vesely (13). Whereas in WASH-1400 common cause failure probabilities were evaluated using upper and lower probability bounds, Vesely showed that common cause failure probabilities can also be evaluated directly by using the

multivariate exponential model developed by Marshal and Olkin (14). For this purpose, Vesely developed a statistical estimation technique for cases where common cause failures are repairable. Two special cases were examined, the constant failure rate case and the binomial failure rate case. A BWR scram system served as an example. In another paper, Johnson and Vesely (15) applied the same technique to the common cause analysis of valve leakages. In both papers, actual data were used from EPRI records and Licensee Event Reports (LER), respectively. It should be noticed that the quantification model used is dependent upon the data populations and presupposes that the components from a given defined population are subject to similar failure causes.

Fleming and Raabe (16) compared GA's approach (14) (known as β-method) to both aforementioned methods (i.e., RSS and Vesely's methods). The objective of their paper was to show the validity of the common cause coupling β-method as compared to the bounding technique of the RSS and the multivariate exponential distribution of Vesely. Modarres et al. (1) has recently studied a method to quantify CCF affect by using a Markovian approach. They used exponential distributions to model and evaluate the failure probability of cutsets due to both random cause and common cause failures. A simplified auxfeed system served as an example, and failure probabilities were close to that predicted by the RSS bounding method.

4. Suggested Work Statement

As discussed in Section 1.0, the main objective of the work proposed here is to develop an efficient tool

with which to characterize common cause failures for reactor safety systems. It is suggested that the proposed work be structured into the following tasks:

Task 1. Acquisition and Implementation of the COMCAN-II and BACFIRE-II Codes

COMCAN-II (2) and its predecessor, COMCAN, are programs for (a) locating common cause candidates and (b) identifying the associated significant common cause events. COMCAN uses fault tree minimal cutsets as inputs for analysis. However, for large fault trees, time and monetary considerations usually require that codes designed for obtaining fault tree minimal cutsets have their outputs restricted to minimal cutsets containing small numbers of events--usually three events or less. Because any number of events might exist simultaneously due to the same secondary cause, an analysis considering only small order minimal cutsets can omit significant dependencies.

BACFIRE-II is the predecessor of the BACFIRE Code. It uses a new methodology suggested by Wagner (17). In this methodology cutsets of intermediate gates that are not common cause candidates are removed and the gate is replaced by a dummy event.

COMCAN-II, BACFIRE-II, and MOCUS-BACFIRE are designed to circumvent COMCAN's limitation of dependence upon the minimal cutsets obtained by other codes. COMCAN-II utilizes the new fault tree cutset generator code FATRAM (18) as a program module, and MOCUS-BACFIRE uses the MOCUS code as its cutset generator. All of these three codes use the generic classification of secondary causes that was developed for the COMCAN Code. Generic

classification of secondary causes results in a finite number of events to be considered. For example, it suffices to search for minimal cutsets susceptible to the generic secondary cause "impact" rather than for those susceptible to "source" of impact such as pipe whip, missile, or earthquake. The generic classification thus bounds the analysis and makes it tractable.

COMCAN-II is written in FORTRAN for CDC CYBER-76 computers and therefore should be run on a CDC machine if possible.* Task 1 would therefore be to obtain the COMCAN-II and BACFIRE-II codes and make them operational. The code MOCUS-BACFIRE is already operating on MIT's IBM 370/168 computer.

Task 2. Assessment and Comparison of MOCUS-BACFIRE, COMCAN-II, and BACFIRE-II Codes

The purpose of this task is to identify the most efficient code for further development. The Code MOCUS-BACFIRE has already been tested and examined for a number of examples (1, 15).

Various examples will serve to accomplish this comparison. For a final decision on which code will be taken for further development by using sample examples, one should consider the following factors

- Convenience with regard to inputting data and reading the output.
- Restriction on the size of the input fault tree.
- Restriction on fault tree logic structure.
- Possibility of changes in different routines of these codes.

- Computation time on the respective computers for a given example (i.e., CPU time)

Finally, based on the findings from this comparison and through close cooperation and consultation with the sponsoring utilities, the most promising code will be selected.

Task 3: Redefinition of Existing Criteria for Identifying CCF Modes and Incorporating Them into The Selected Code Described in Task (2)

The criteria used in COMCAN-II, BACFIRE-II and MOCUS-BACFIRE for identifying a cutset as a CCF are similar. They are as follows:

(1) A cutset is a common cause candidate if all the basic events in that cutset are associated by a condition which alone may increase the possibility of multiple component malfunction. An example of a common cause special condition would be all components implied by the basic events of a minimal cutset having been installed by the same construction crew, or all sharing a common power supply or manufacturer.

(2) A cutset is a common cause candidate if all the basic events in that cutset are susceptible to the same secondary failure cause and are located in the same domain for that cause of secondary failure. For example, if all the components implied by the basic events in a minimal cutset fail when exposed to excessive heat and no barrier to heat exists between the components, the cutset is identified as a common cause candidate.

Recent studies (1, 12, 19) have shown that in some cases important dependencies in the cutsets or sequences of failures may be ignored by using above criteria. For example, for the case of a complete loss of a.c. power one needs both diesel generators and off-site power to fail. That is

D.G.1, D.G. 2, L.O.P.

However, a great number of dependencies exist between the two diesel generators, but not between loss of offsite power and the two diesel generators. The following dependencies can exist between the two diesel generators:

- Common maintenance crew
- Common manufacturer
- Common heat barrier
- Common mechanical vibration barriers, etc.

However, by using the aforementioned criteria, the loss of complete a.c. power sequence will not be identified as a common cause candidate due to only partial dependencies and not complete dependency among sequences of events. This would result in a major miscalculation in probabilities of complete blackout. The random failure of each diesel generator is estimated to be 1/58 per demand (16). The frequency of the loss-of-offsite power is estimated to be 0.2/year. Therefore, the total loss of a.c. power due to random failures would be approximately 5.8×10^{-5}/year. By taking into account the effect of dependencies between the two diesel generators one finds the failure probability of the two units, using the β-factor method, to be 2×10^{-3}/demand (16). Therefore, the total loss of a.c. power

probability would be $(2 \times 10^{-3}) \times (0.2) = 4.0 \times 10^{-4}$/year. It is obvious that by ignoring the dependency between the two diesel generators the a.c. system failure probability would be underestimated by a factor of about 10.

To identify any dependency it is suggested that the following criteria be used:

(1) A cutset is a common cause candidate if <u>any two or more</u> of the basic events in that cutset are associated with conditions which alone may increase the probability of multiple malfunction.

(2) A cutset is a common cause candidate if <u>any two or more</u> of the basic events in that cutset are susceptible to the same secondary failure cause <u>and</u> are located in the same domain for that cause of secondary failure.

The number of minimal cutsets that are identified as common cause candidates using above criteria would result in an increase in the number of common cause candidates compared to the old criteria, because any dependency among components of the cutsets would be identified. It is important, however, to eliminate those cutsets whose contribution to the total system failure is negligible. For this reason one might use a probability CUTOFF value to eliminate any cutset having an unavailability of less than this value. For example, if ABCDE is a common cause candidate because of dependency between A and B, but random failure probability of C x D x E is less than the CUTOFF value, then ABCDE may be eliminated.

Task 4: Selection and Incorporation of a Potential Common Cause Failure Quantification Technique

Common cause failure quantification techniques are discussed in detail in reference (6). The most promising techniques are Vessely's Marshal-Olkin specialization (13), β-Factor (16), and RSS bounding (4) technique. Marshal-Olkin specialization technique is capable of estimating CCF rates from scarce data. The method is very complex and is mainly applicable to scarce data.

The β-Factor method allows proper probabilistic treatment of CCF by separating the depency contribution among components of the system. Data can be synthesized when directly applicable data are scarce. However, the method is limited by existing data to only redundant systems.

The RSS bounding technique has been applied and presented for most of the reactor safety systems in the WASH-1400 study. The accuracy of this system is questionable for some special cases (20). A recent study (16) has compared the β-Factor method with the RSS bounding and Marshal-Olkin specialization techniques. It is shown in this study that the β-Factor and Marshal-Olkin methods are consistent. However, some differences exist between probabilities predicted by the β-Factor and the RSS bounding technique.

In a recent study at MIT by Modarres et. al. (1), a quantifying methodology has been proposed. In this technique the common cause candidates that are obtained by using the new

criteria described in task 3 are used to quantify the safety systems. This technique is based on the Markovian approach. Similar to other quantifying methods, lack of data base is its most important limitation. Its methodology is fairly complex.

In this task a review of these potential quantifying methods will be made. A promising technique will be selected for incorporation into the CCF code. Possible changes in the methodology might be required in order to properly implement the selected methodology into the code.

Task 5: Application of this Study to the Problems of Interest

This task will be performed with a close cooperation of the sponsors. The task includes the following steps;

- selection of a particular safety system;
- development of its fault tree diagram;
- identification of desired generic failures;
- generation of the cutsets along with their potential common cause candidates by using the developed code;
- quantification of the system unavailability by using data from the recent NRC data (21) obtained from the Licensee Event Reports (LERs).

Common Cause Budget
10/1/81-9/30/82

	10/1/81#-- 6/30/82	7/1/82#-- 9/30/82
Salaries and Wages		
Principal Investigators		
C. Heising-Goodman (1.2mm Acad. Year	3,004	413
1mm Summer '82)		3,178
N. Rasmussen (0.26mm Acad. Year	1,390	211
0.24 Summer '82)		1,621
Secretarial (1.8mm)		2,200
Research Assistant	12,654	4,770
Administrative*	1,705	1,239
Total Salaries & Wages	18,753	13,632
Employee Benefits**	1,702	2,472
Indirect Expenses***	9,717	9,712
Materials and Supplies	1,900	950
Computer	1,333	667
Travel		1500 ~~2,000~~
Report Preparation		500 ~~2,000~~
	$33,405	$31,433

TOTAL $64,838

Notes:

*Allocated project level costs and program coordination at 10% of other salaries and wages.

**27.9% of non-student salaries and wages.

***72% of total salaries and wages plus employee benefits minus 55% of student research assistant salaries and wages through 6/30/82; after 6/30/82, 51.5% of Modified Total Direct Cost (includes salaries and wages, employee benefits, materials and services, travel, services, subgrants and subcontracts up to $25K each, less 60% research assistant salaries and wages, less equipment with unit cost of $500 and useful life of 2+ years).

#The budget is shown broken into two parts merely for accounting convenience; this is not a phased project.

Computer Expenses

The comparison of the codes will be accomplished on the IBM system at MIT if conversion from CDC can be accomplished with little or no problem. If the conversion is difficult, the code comparison will be done on the basis of criterion not related to execution time; the codes designed for the CDC system will be run on the CDC machine, and the IBM codes will be run on the IBM machine. If the CDC codes are not easily converted to the IBM machine and one of the CDC codes is selected as most promising, further effort will be made to make the conversion to IBM.

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(21) W. Vesely, Private communications (January 1980).

F.4 Follow-On Work Proposal of July, 1982

Research Proposal

COMMON CAUSE ANALYSIS METHODS FOR LARGE SCALE UTILITY PRAs

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(617) 253-5119

Submitted by:

Energy Laboratory
and
Department of Nuclear Engineering

Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

July 1982

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1. Objectives of the Proposal

The main objective of the proposed research is to develop methods for common cause analysis useful in utility large-scale probabilistic risk assessments (PRAs). Previous emphasis at M.I.T. in common cause analysis research has been primarily on code development for utility systems reliability analysis.[1,2,3] Advantages of this approach include provision of a systematic framework for performing detailed analysis of system reliability. However, fault tree analysis on the level of detail taken in such specific system studies may not be required for every system studied in a large-scale, complete PRA of the entire plant. As has been shown in the Zion study[4], methods for reducing fault tree size and level of detail have been developed and applied in performing plant specific, large-scale PRAs. Thus, a simplified approach to common cause analysis may be desirable in a large-scale utility PRA for reasons of reduced cost and enhanced use of available data.

2. Expected Benefits

The expected benefits for the utilities are to obtain methods, which will be encoded into a computer package, for performing common cause analysis in a large scale plant specific PRA. This code will constitute an alternative to the very detailed analysis represented in the MOBB package developed for extended systems reliability studies at M.I.T.[1,2,3]

3. Proposed Methodological Approach

The method that we propose to study and develop into a tool for large-scale PRA common cause analysis is that of the combined cause-table and discrete-probability-distribution (DPD) approach. These methods have been primarily utilized in the Z/IP studies, and have been described in the available literature.[5,6] To describe further our proposed approach it is necessary to begin with a few definitions and then expand further into how the cause table is applied, and how DPD arithmetic is used in external event analysis. We shall do this now. (The following description comes from reference 7.)

The cause table was developed in the Z/IP study to help structure the process of enumeration and analysis of failure causes for combinations of component failures (ie., minimal cutsets). It formalizes the necessary steps in the systems analysis process between the point of determining the cutsets to the point of having an algebraic expression for the system unavailability (or other reliability performance characteristic). The cause table idea provides a "jumping off" point in our study of common cause failures.

An example cause table of a hypothetical system having seven components given the letters A through G is presented in Table 1. The system in the example has two single component cutsets, one with two components and one with three components. In Part I, information about the accident sequences in which the system is demanded and which establish the boundary conditions of the system analysis is compiled. Failure causes acting on the components singly are itemized in Part II, and the common causes of multiple failure in Part III. Common cause failures are always enumerated

TABLE 3-1. EXAMPLE CAUSE TABLE FOR CAUSES AFFECTING SINGLE AND MULTIPLE COMPONENTS

SYSTEM: Sample
COMPONENTS: A, B, C, D, E, F, G
MINIMAL CUTSETS: A, D, BC, EFG

Part I - Accident Sequence Dependent Boundary Conditions			
Initiating Event	Accident Sequence	Interfacing Systems Failures and Boundary Conditions	Changes in Internal and External Environment

Part II - Single Failure Cause Sets							
Cause Category	Components						
	A	B	C	D	E	F	G
Hardware Environmental Test Maintenance Operator Error Other							

Part III - Multiple Failure Cause Sets					
Cause Category	Component Failure Sets				
	BC	EF	FG	EG	EFG
Human Interactions Design Error Manufacturer/ Installation Error Operator Error Test/Maintenance Error Physical Interactions Excessive Temperature Excessive Pressure Excessive Vibration Excessive Impact Corrosive Agent Excessive Moisture Other					

in the cause table such that the single point failures show up as single event cutsets in the system model and associated logic function.

The second half of the methodological approach is associated external event analysis and DPD arithmetic. In a sense, external events constitute both initiators of accidents and a possibility for common cause failure. It is possible to extend the fragility curve concept to other types of common causes; human error, corrosion, environmental stresses, etc.* We propose to attempt to extend the Beta-Factor concept by using the DPD-fragility curve-external event analysis technique. It may be possible to define Beta Factor Functions that represent the susceptibility of a particular component type to the particular environmental cause of failure present. That is, along any particular accident sequence (i.e.; path in the systems event tree), a different environment may be implied due to various system failures so higher humidity, more corrosive materials in air due to particulate production and fission product releases, etc.). These effects can produce higher Beta-Factors resulting in higher system unavailabilities (i.e., higher system failure rates).** By using Beta "functions" that systematically take into account the effect on components of each environmental cause, a more systematic procedure can be developed for estimating the effect on the overall system failure rate (unavailability). The concept of the Beta Factor Function can perhaps, allow for a better characterization of

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*This point is recognized in Section 3.7 of the NRC PRA Procedures Guide written by K. Fleming of Pickard, Lowe, and Garrick, Inc. These Mr. Fleming describes, categories of dependent failures noting that to model physical interactions that result in multiple system/component failures with event specific models is entirely legitimate.

**WASH-1400 handled this problem by increasing the system failure rates along the event tree using expert judgement.

system dependencies in the event trees, upon which the results of a large-scale PRA depend (see Figure 1).

Suppose failure of system A produces a heavy steam environment; how does the failure rate of system B change as a result, i.e.: how does the ratio

$$\frac{\phi \quad \{B_f|A_s\}}{\phi \quad \{B_f|A_f\}} \quad \text{change?}$$

What is the ratio of random to system dependent failure rates (given functional operation of system B is independent of system A). The answer to this question could be simply derived directly from expert opinion (ie., failure rate of B directly estimated by experts) or the question could be asked on a sub-system (or component/cutset) level. The system cause table can be modified as the event tree is analyzed to facilitate this process.

Suppose now that system C has a failure rate dependent on steam and corrosion as possible causes that increase the failure rate (Figure 2). Suppose systems A and B fail and produce this environment; now $\phi\{C_f|B_f,A_f\} = 1$ if these conditions exceed the design limit of C for these environmental conditions.

For purposes of illustration, imagine that we have a specific component or system, S, at a specific location in the plant, L, and wish to know the risk of failure of this component or system due to changes in the environment (corrosion, temperature and/or humidity changes, etc.). We first need a statement of how

FIGURE 1 System Dependencies Modelled in Event Trees

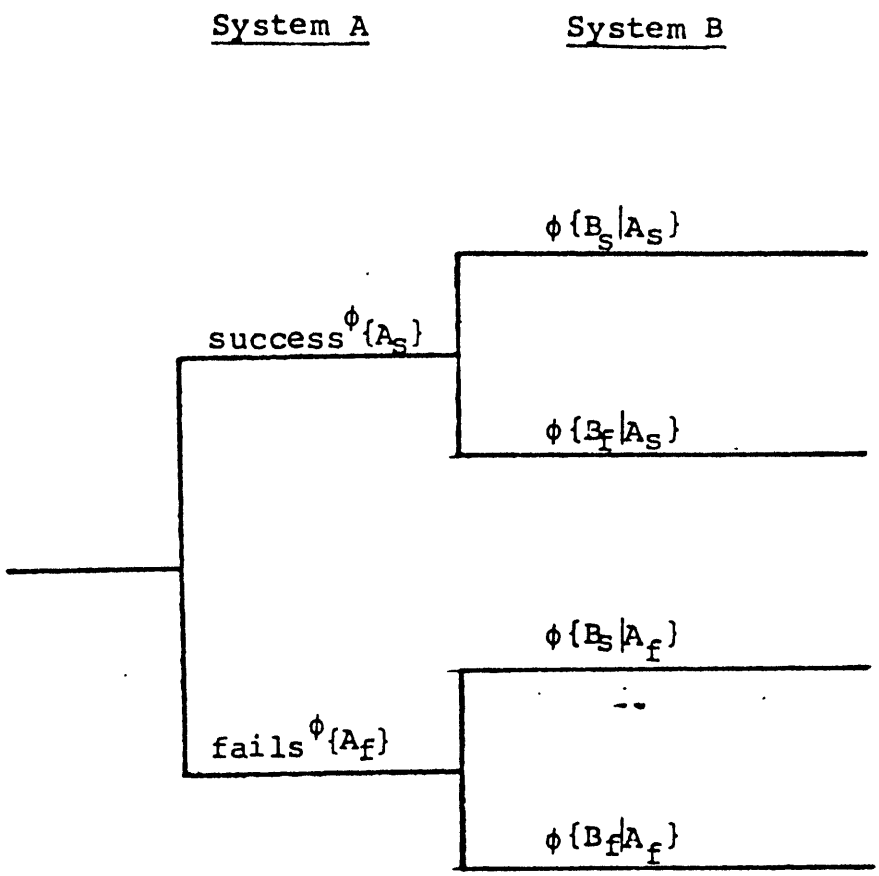
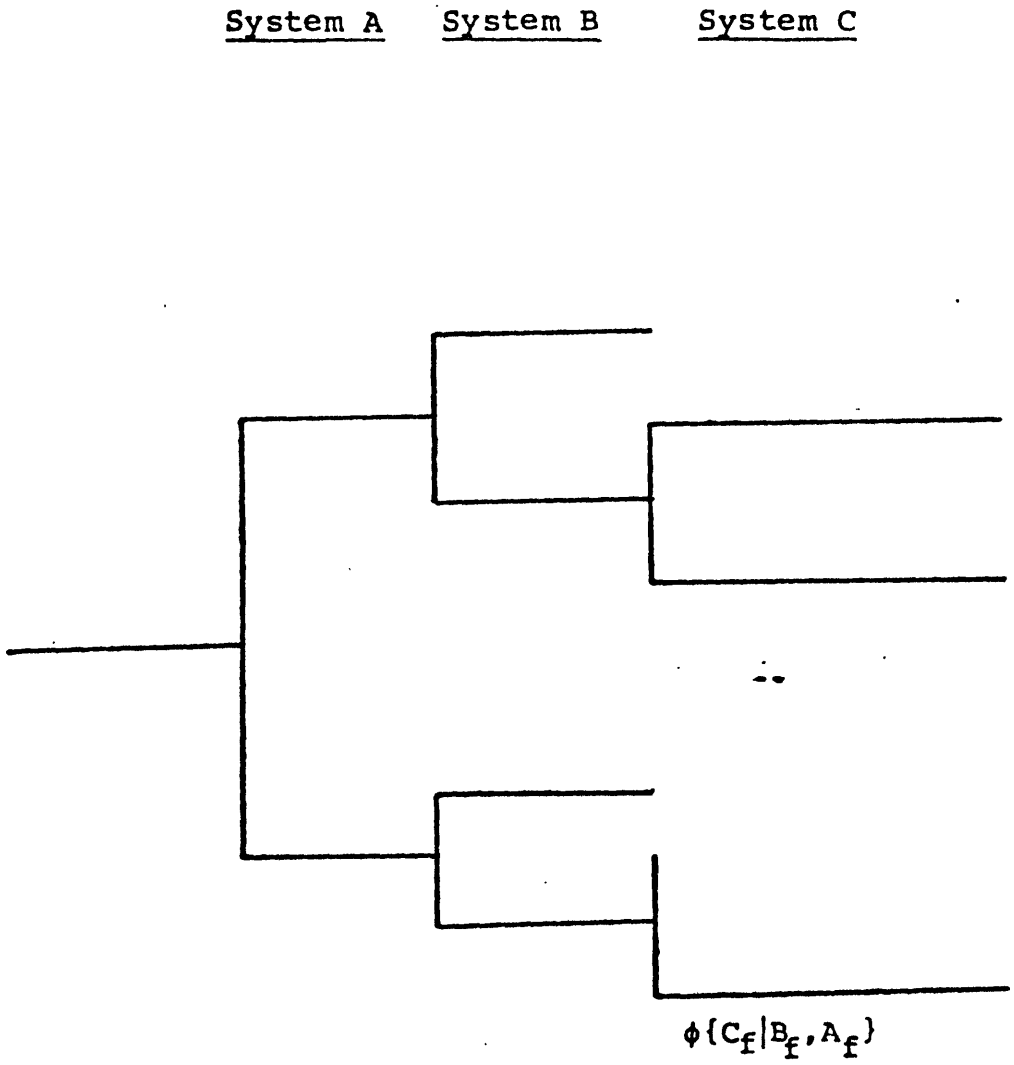


FIGURE 2 Introduction of Third System Dependency



likely it is that the environment will change. This could be done by expressing the information in the form of a frequency of exceedance curve (see Figure 3). The ordinate of this curve over any value, x, gives the frequency with which environments of severity "x" or greater occur at the location L.*

The second item of information needed is a characterization of the ability of the component or system to resist environments of various severities. This characterization can be done in the form of a cumulative distribution function that maps, F, the component or system failure fraction against the severity of the environment, x (see Figure 4). The ordinate here, F(x), gives the fraction of components or systems failing under environmental severity "x".

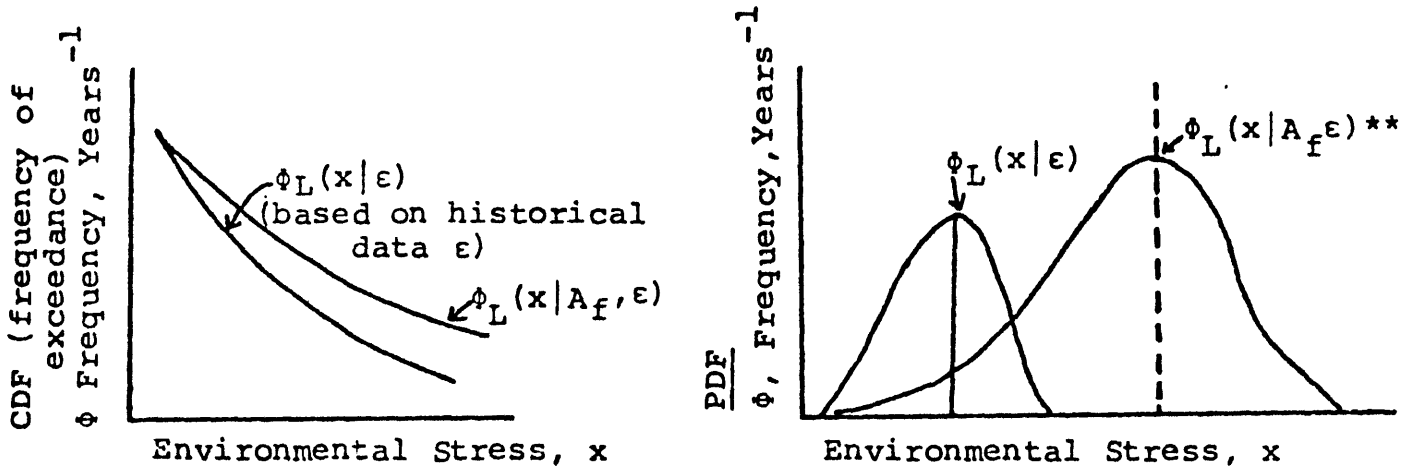
Specifically, what this means is that we envision a thought experiment in which thousands of systems (components), S, are subjected to environmental stresses of magnitude "x" and type i.e.; $F(x_i)$ is then the fraction that fails in this experiment. (Data of this nature are generally available from component manufacturers; on the system level, some information of this nature is also available).

Now assume that we had run the experiment and know the curve $F(x_i)$ exactly. Similarly, suppose we had monitored the location in the plant for many years and knew the curves $\Phi(x_i)$ exactly. Then, the frequency of system failure, f_Φ, due to environmental stress i would be given by:

$$f_\Phi = -\int_0^\infty \frac{d\Phi}{dx} F(x)\,dx \qquad (1)$$

*We can also express the effect of system A failure on the frequency of observing condition x as $\phi_L(x|A_f,\varepsilon)$ at location L given historical experience ε.

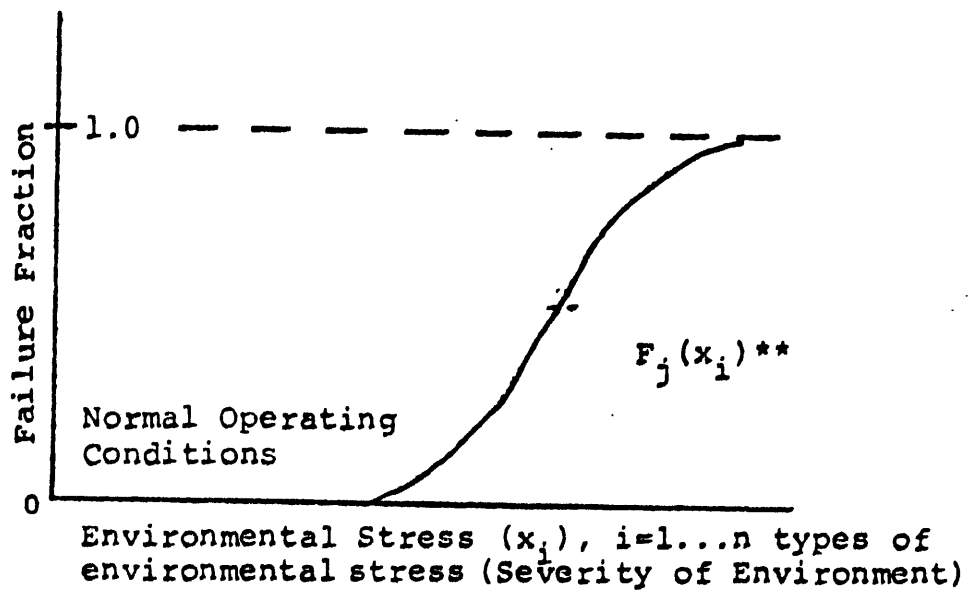
FIGURE 3 Environmental Stress Curve (CDF and PDF forms)*
(Frequency of Observing a Particular Severe Environment x at Location L).



**Likelihood of Observing Environmental Condition, x, Give System A Fails.

*Corresponds to Seismicity Curve in Seismic Analysis

FIGURE 4 System/Component Environmental Susceptibility Curves*



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*Corresponds to Fragility Curves in Seismic Analysis; Data acquired from manufacturers for environmental stress i.

**$F_j(x_i)$ $\triangleq$ ability of system j to resist various levels of enviromental stress type i.

The variable f_Φ may be regarded as the quantitative measure of environmental stress related risk to S at L. Thus, by evaluating the integral in (1), we could calculate the answer to our question.

Probabilistic Calculation

Following Kaplan [6] once again, let us acknowledge that we really do not know the environmental stress curves $\Phi(x)$ exactly. We can, however, use the DPD idea to express our uncertainty in $\Phi(x)$ by putting forth a finite family of curves, $\Phi_k(x)$, and assigning to each a probability p_k. Thus, we have a set of doublets:

$$\Phi \equiv \{<p_k, \Phi_k(x)>\} \tag{2}$$

which we may plot graphically as in Figure 5.

Similarly, since we have not done a "real" experiment, we do not know the environmental susceptibility curves perfectly. We therefore express our state-of-knowledge about susceptibility by writing a DPD:

$$F \equiv \{<q_e, F_e(x)>\} \tag{3}$$

Pictorially, we have the family:

FIGURE 6 Susceptibility Family

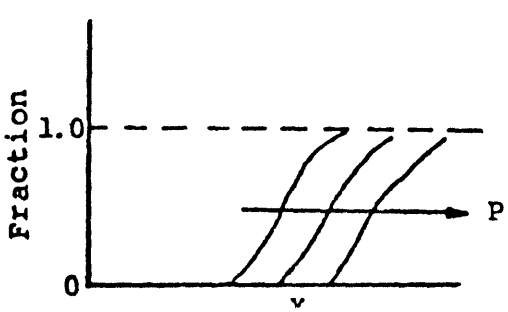
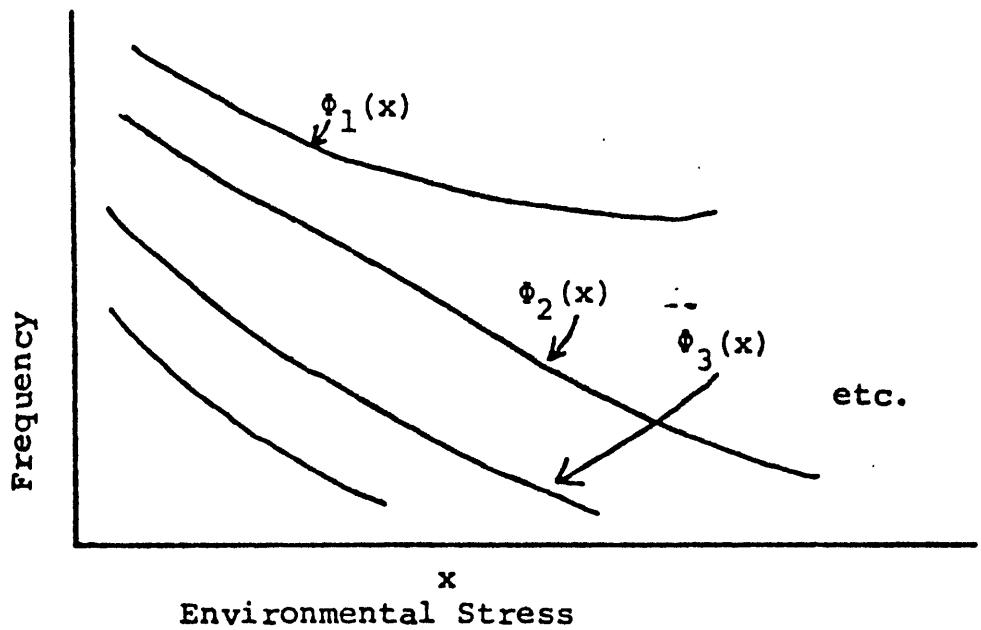


FIGURE 5 Environmental Stress Curves Including Uncertainty



We next perform the operation of equation (1) on the DPDs (2) and (3) obtaining thus the DPD:

$$F_{\Phi} = \{<P_{kl}, f_{kl}>\} \tag{4}$$

where

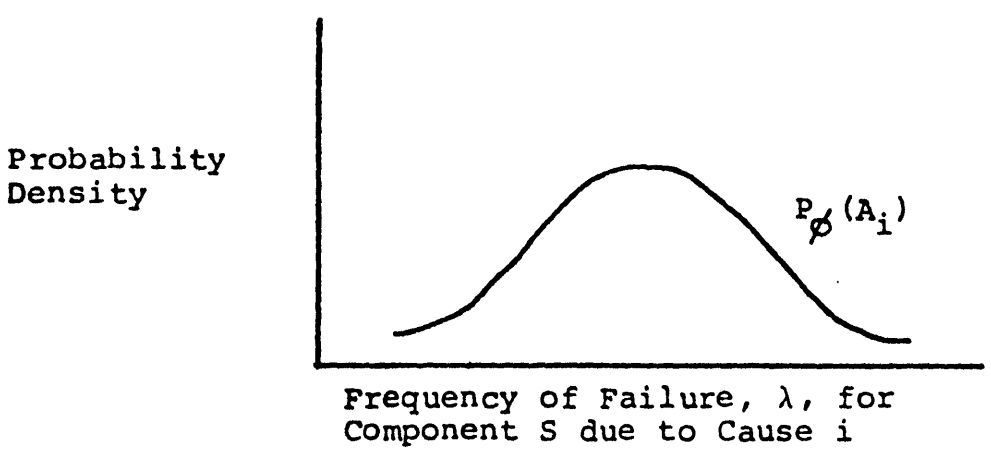
$$P_{kl} = P_k q_e \tag{5}$$

and

$$f_{ij} = -\int_0^{\infty} \left(\frac{d\Phi_k}{dx}\right) F_e(x)\,dx \tag{6}$$

The DPD (4) can now be smoothed and plotted as a PDF:

FIGURE 7 Probability of Failure Frequency (Due to Environmental Stress Type i)



Outputs of DPD/Seismic Analogy (DPD-SA) Model

(1) Method for estimating β factors for use as input into CCA code package (MOBB).

(2) Method for treating system non-functional dependencies in the accident event trees so as to provide a systematic way to change the system failure rate calculated from fault trees (based on cause table inputs) to account for these dependencies. (Method for estimating failure frequencies in cause table.)

How to Relate to Cause Table

(1) Use cause table to determine which causes to perform the DPD-SA analysis on, and

(2) Cause table helps organize expert's thoughts and provides a way to document such thinking.

4. Suggested Work Statement

We shall perform the following tasks:

TASK 1: Develop and refine, for practical use by utility analysts, the cause table/DPD approach to common cause analysis described in section 3 of this proposal.

TASK 2: Develop an analytic package based on the approach of section 3 to estimate cause-specific Beta-Factors compatible with the MOBB code developed in earlier work.

TASK 3: Demonstrate the use of the cause-table/DPD approach in application to a system example provided by the utility sponsors.

TASK 4: Perform a comparison of the results of this approach with the more detailed approach making use of the MOBB code package with and without the Beta-Factor estimation methods developed in Task 3.

5. Key Dates and Reports

The effort will involve a one year project that will accomplish the following:

(1) Completion of Tasks 1 and 2 - producing an analytic package (computer program routine) to estimate cause-specific Beta Factors that is compatible with MOBB . (first 5-6 months).

(2) Completion of Task 3 - demonstrates the use of the cause table/DPD approach on a sample utility system. (2-3 months).

(3) Completion of Task 4 - comparison of the results of this approach with standard MOBB code approach (2-3 months).

The product of the project will be a final report and an analytic package for estimating Beta factors based on the cause table/DPD approach. A user's guide on the package will also be provided. These will be provided within 3 months after the project completion. A proposed budget is provided on the following page.

Budget
(10/1/82-9/30/83)

SALARIES & WAGES		
Principal Investigator		
C. Heising (20%)		
Graduate Research Assistant (100%)		
Secretary (15%)		
Administrative*		
	TOTAL S&W	32,398
EMPLOYEE BENEFITS**		3,731
INDIRECT COSTS***		18,742
MATERIALS & SERVICES		3,240
COMPUTER (IBM 36/370)		5,000
DOMESTIC TRAVEL		2,000
REPORT PREPARATION		2,000
	TOTAL	$67,111

Notes:

*Allocated project level costs and program coordination at 10% of other S&W.

**30% of non-student S&W.

***51.5% of Modified Total Direct Cost (includes S&W, employee benefits, M&S, travel, services, subgrants up to $25k each, less 60% research assistant S&W, less equipment with unit cost of $500 and useful life of 2+ years.

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2. Heising, C.D., Karimi, R., Mak, C., Modarres, M., Rasmussen, N.C., and Wolf, L, User's Manual for MOCUS-BACFIRE: A Computer Program for Common Cause Failure Analysis, MIT-EL-81-037, Electric Utility Program, November 1981.

3. Mak, C. Heising, C.D., Modarres, M., "Application and Extension of the MOCUS-BACFIRE Common Cause Analysis Code to Reactor Safety Systems", Session IV-B, Common Mode Failures, International ANS/ENS Topical Meeting on Probabilistic Risk Assessment, Port Chester, New York, September 20-24, 1981.

4. The Zion Probabilistic Risk Study, Westinghouse/PLG, 1981.

5. Methodology for Probabilistic Risk Assessment of Nuclear Power Plants, PLG-0209, June 1981.

6. Kaplan, S., "On the Method of Discrete Probability Distributions in Risk and Reliability Calculations - Application to Seismic Risk Assessment", PLG-0210.

7. Fleming, K., personal communication, March 1982.