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SUBSYSTEM FRAGILITY

Seismic Safety Margins Research Program (Phase I)

Robert P. Kennedy, Robert D. Campbell, G. Hardy, and H. Banon –
Structural Mechanics Associates

Prepared for
U.S. Nuclear Regulatory Commission

Lawrence
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ABSTRACT

Seismic fragility levels of safety related equipment are developed for use in a seismic oriented Probabilistic Risk Assessment (PRA) being conducted as part of the Seismic Safety Margins Research Program (SSMRP). The Zion Nuclear Power Plant is being utilized as a reference plant and fragility descriptions are developed for specific and generic safety related equipment groups in Zion. Both equipment fragilities and equipment responses are defined in probabilistic terms to be used as input to the SSMRP event tree/fault tree models of the Zion systems.

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Executive Summary

Seismic capacities (fragilities) of safety related equipment are developed for use in the Seismic Safety Margins Research Program (SSMRP). The SSMRP is being conducted by the Lawrence Livermore National Laboratory (LLNL) for the U.S. Nuclear Regulatory Commission (NRC). The SSMRP centers around a Probabilistic Risk Assessment (PRA) of a pressurized water reactor for the purpose of developing seismic risk methodology. The Zion nuclear power plant, located in Zion, Illinois, is utilized as a reference plant in the study.

Probabilistic seismic fragilities are developed for both generic and Zion specific equipment. Fragilities are defined for the lowest level failure modes considering both function and structural modes of failure. Seismic fragilities are presented in terms of frequency (or fractile) of failure as a function of a fragility parameter represented by a seismic response quantity. The fragility parameters chosen reflect seismic response quantities being calculated by LLNL. For piping systems, the appropriate response quantity is moment induced by seismic inertial load. For floor mounted equipment, the appropriate response quantity is spectral acceleration associated with the equipment fundamental frequency. Similar fragility parameters are applicable to other equipment such as line mounted valves, vessel nozzles, etc.

No new stress or functional analyses are conducted in the development of equipment fragilities. In cases where original design reports were available for review, fragilities are developed by scaling design analysis results to estimated failure levels. In many cases, design reports were not readily available and fragilities are developed by other methods from information available in the form of design requirements, achieved test levels, military shock test fragility data, topical reports and historical performance.

A significant part of the study focusses on the derivation of generic fragility descriptions from shock test data generated by the U.S. Corps of Engineers. The Corps of Engineers conducted fragility tests and high acceleration proof tests of hundreds of electrical and mechanical equipment items similar to equipment installed in nuclear power plants. They also developed a pseudo-probabilistic methodology to define lower bound fragilities of generic classes of equipment. The test data and methodology are utilized in this study, where applicable, to develop generic fragility descriptions of equipment.

In the SSMRP, variability, associated with both equipment capacity and equipment response are separated in order that the sensitivity of individual variables to the overall seismic risk can be assessed. Accordingly, the fragility descriptions presented reflect only the variability associated with equipment capacity, given a response to a specified input. For each specific item of equipment or generic category of equipment, an associated response factor is developed that describes the degree of conservatism or unconservatism in the calculated response and the variability associated with the response factor.

Fragilities, response factors and their variabilities are defined in terms of lognormal distributions. The variabilities are separated into random variability and variability due to uncertainty in given or estimated values of the variables that contribute to capacity or response. In addition to the lognormal fragility description of all components, fragility descriptions developed from Corps of Engineers shock tests data are developed assuming both normal and lognormal distributions.

An important observation that can be made from the final fragility descriptions is that most mechanical and electrical equipment is inherently rugged and will survive acceleration levels far in excess of building responses associated with the Safe Shutdown Earthquake (SSE) regardless of whether the equipment was qualified for seismic service. Equipment and supports that fail in a structural mode, and which have had specific designs to resist seismic loading, typically have median capacities of several times the SSE level of earthquake specified for design. The residual capacity is due to the inherent safety factors in governing codes and standards and conservatism employed in computing equipment response during the design process.

The largest source of uncertainty in the derived fragility levels arises from lack of detailed knowledge regarding actual material properties, failure modes, load distributions and response variables. Sensitivity to overall seismic risk is not a part of this study; however, the fragility and response information is presented in a form such that sensitivity studies could be carried out to assess the significance of uncertainties.

1.0 INTRODUCTION

The Seismic Safety Margin Research Program, sponsored by the United States Nuclear Regulatory Commission, has a prime objective of developing methodology and mathematical models that realistically predict the probability of radioactive releases from seismically induced events in nuclear power plants. The overall SSMRP program plan is described in Reference 1.

There are eight major projects in the SSMRP program which cover the major engineering disciplines that are integrated into the overall seismic risk methodology. These projects are:

(I) Plant Site Selection and Data Collection
(II) Seismic Input
(III) Soil-Structure Interaction
(IV) Structural Building Response
(V) Subsystem Response
(VI) Fragility
(VII) System Analysis
(VIII) Load Combination

This report addresses parts of Projects V and VI. In Project V, the variability of computed response to seismic excitation for components and subsystems is addressed. In the case of piping systems and major components of the NSSS, Lawrence Livermore Laboratories (LLL) will conduct multiple time history analyses for increasing seismic excitation levels in order to quantify the probabilistic distribution on computed response. For safety-related systems and components which will not be reanalyzed, a probabilistic description of the response, as computed in the original design analysis, must be developed to identify the degree of conservatism or unconservatism in each of the variables that contributes to calculated response and to quantify the variance in computed response. Structural Mechanics Associates, Inc., (SMA), is charged with this latter part of Project V.

In Project VI, the fragility of of structures and subsystems is to be developed and described in probabilistic terms. SMA is charged with developing fragility descriptions for both structures and subsystems. The structures fragility descriptions are reported in a separate document, Reference 2. This report deals with the development of fragility descriptions for safety-related subsystems and components.

The Zion nuclear power plant is the reference plant selected for the SSMRP. Zion Units 1 and 2 are 1100 Mw pressurized water reactors operated by Commonwealth Edison Company. The NSSS supplier was Westinghouse Electric Corporation and the Architect Engineer was Sargent and Lundy Engineers. Zion structures and equipment were designed for an operating basis earthquake of 0.08g peak ground acceleration and a design basis earthquake (analogous to a safe shutdown earthquake) of 0.17g peak ground acceleration. The original seismic design criteria are documented in the Final Safety Analysis Report, (FSAR), Reference 3.

Much of the plant specific information, regarding the plant subsystems and components designs, has been supplied to the Lawrence Livermore National Laboratory by the Utility, NSSS supplier, and Architect Engineer. It was not feasible in Phase I of the SSMRP to obtain and evaluate detailed design information for all safety-related equipment to be considered in the risk model. Consequently, a generic treatment of much of the equipment was necessary. As a result, when fragility descriptions and subsystem response descriptions are developed generically, the uncertainty, due to lack of detailed information, is generally increased from those descriptions developed with plant specific information. This uncertainty is quantified and is included as part of the fragility and subsystem response descriptions.

2.0 TECHNICAL APPROACH AND INTERFACES

In development of fragility relationships for subsystems and equipment and probabilistic distributions of subsystem response, the concept of capacity factors and response factors is used. These factors represent factors of conservatism or unconservatism in the design codes, design loading and subsystem response calculations, i.e., they are factors of safety above the original seismic design bases of the equipment. Once the factors of safety are established, the capacity (fragility) can be derived as the product of the safety factors times the original seismic design basis acceleration or load. This general procedure is used for equipment that was designed by analysis and for which detailed design information was available or could be reasonably estimated.

2.1 FRAGILITY DESCRIPTION AND INTERFACE WITH STRUCTURAL RESPONSE PROJECT

The derived fragility is expressed as a cumulative distribution function (CDF), commonly referred to as a fragility curve. The fragility curve is a plot of frequency of failure as a function of some fragility parameter, Figure 2-1. The fragility parameter is chosen to coincide with a response value that will be calculated in the structural response or subsystem response programs. For floor and wall mounted equipment, the appropriate fragility parameter is spectral acceleration, S_a, for flexible equipment and zero period acceleration, ZPA, for rigid equipment. In some special cases, other fragility parameters will be specified such as moment or force.

In cases where spectral acceleration is specified as the appropriate fragility parameter, an associated frequency and damping must be specified. The damping value specified will be that value considered to be a median value for the subsystem under consideration and will generally not be the conservative value of damping specified for design. Median damping and the variability on response due to damping variability are quantified in Chapter 5, Subsystem Response.

In many cases, the exact equipment fundamental frequency is not known and a range must be estimated. In order to account for the effect of the variability in spectral acceleration on the frequency of failure over the estimated frequency range, a response post-process routine should be incorporated to account for the probability of occurrence of the frequency and the associated spectral acceleration.

The base motion for equipment in a plant depends not only on the actual earthquake record, but also on the structural response. A distribution of the spectral acceleration, S_a, will be defined in the structural response program, Figure 2-2. Curves such as the one depicted in Figure 2-2 will be derived by calculating the response to many input motions and by varying parameters that affect structural response. The fragility project will develop probabilistic models for resistance so that later, by integrating the uncertainty in the input spectral acceleration with the uncertainty in resistance, the probability of equipment failure can be calculated.

The cumulative distribution function (CDF) of failure (Z) will be specified as a function of input spectral acceleration, Figure 2-1, where the failure event (Z) is a (0,1) random process. In the calculation of the probability of equipment failure, the uncertainty in the input spectral acceleration must be combined with the uncertainty in resistance.

$$F_Z \left[z|\omega^*\right] = \int_0^\infty F_Z \left[z|S_a(\omega^*)\right] \quad f_{S_a} \left[\dot{s}_a \ (\omega)\right] d \ s_a \qquad (2\text{-}1)$$

In cases where the natural frequency (ω *) of the equipment cannot be exactly determined, it will be necessary to take this source of uncertainty into account. Usually, one may limit ω* to lie between a lower and an upper bound (ω_1, ω_2).

$$F_Z \ (z) = \int_{\omega_1}^{\omega_2} F_Z \ (z|\omega^*) \ f_{W^*} \ (\omega^*) \ d\omega^* \qquad (2\text{-}2)$$

The simplest way to handle this is to assume that the distribution of * is uniform between $\omega_1 - \omega_2$. In this case:

$$f_{\omega^*} \ (\omega^*) = \frac{1}{\omega_2 - \omega_1}$$

and the probability of failure may be computed by simply averaging $F_Z \ (z|\omega^*)$ at given values of ω^* $(\omega_1 < \omega^* < \omega_2)$.

If other than a uniform distribution of ω^* is assumed, then the above integral must be carried out numerically.

In specifying the fragility parameter as spectral acceleration within a frequency range, $\omega_1 - \omega_2$, it is anticipated that the structural response or systems analysis projects will incorporate the above methodology to account for uncertainty in the exact frequency. The uncertainty on exact frequency could be incorporated into the fragility curves via response factors based upon the original design spectra. However, since new spectra will be generated in the structural response project, which will likely not have the same shape as the original design spectra, the more appropirate method is to operate on the newly computed responses as indicated above. The response factors in Chapter 5 do not, therefore, take into account uncertainty in fundamental frequency as it may affect spectral acceleration.

2.2 DEVELOPMENT OF SAFETY FACTORS

Development of seismic safety factors, associated with the design basis earthquake, is based on consideration of several variables. The variability of dynamic response for a specified acceleration and the variability in the structural capacity of the subsystem are the two basic considerations in determining the overall variability in the factor of safety of a component. Several variables are involved in determining both the subsystem response and the subsystem capacity and each such variable, in turn, has a median factor of safety and variability associated with it. The overall factor of safety is the product of the median safety factors of all of the variables. The variabilities of the individual variables also combine to determine variability of the overall safety factor.

Variables influencing the factor of safety on subsystem capacity, to withstand seismic induced vibration, include the strength of the subsystem compared to the design stress level and the inelastic energy absorption capacity (ductility) of a subsystem; i.e., its ability to carry load beyond yield. The variability in computed subsystem response for a given in-structure response spectrum is made up of many factors. The more significant factors include variability in 1) energy dissipation (damping), 2) subsystem modelling, 3) method of analysis, 4) combination of modal responses and 5) combination of earthquake components. The ratio between the median value of each of these factors and the value used in design of the Zion Plant and the variability of each factor are quantitatively estimated in Chapters 4 and 5 for various subsystems and equipment. These estimates are based on available analyses and test data for Zion, limited new analysis, generic tests and engineering judgment derived from experience in the analysis of nuclear power plants and components.

2.3 DEFINITION OF FAILURE

In order to estimate the median factor of safety against subsystem or component failure from the original seismic design basis, it is necessary to define what constitutes failure.

Piping, electrical, mechanical and electro-mechanical equipment, vital to a safe shutdown of the plant, are considered to fail when they will no longer perform their designated functions. Rupture of the pressure boundary for pressurized fluid and gas systems is also considered a failure as well as failure of the equipment supports. Therefore, for some equipment, several failure definition exist; (failure to function, pressure boundary rupture and support failure). Depending upon the equipment type, one or the other definition will usually dominate. In most cases, however, the function failure definition will govern, as equipment pressure boundaries and supports are usually very conservatively designed for equipment such as pressure vessels, pumps and valves. For piping, failure of the support system or plastic collapse of the pressure boundary are considered to represent failure and the inelastic energy absorption limits (ductility limits) associated with these failure modes have been estimated in order to define the margins of safety.

2.4 BASIS FOR SAFETY FACTORS DERIVED IN STUDY

There was a general lack of detailed information available on seismic fragility of subsystems and equipment for use in this study. Therefore, most median safety factors, estimates of variability and conditional probabilities of failure, estimated in this study, are based on limited existing analyses and qualified engineering judgment and assumptions. Some limited additional analyses were conducted to evaluate the expected failure capacities of the diesel oil storage tanks, condensate storage tanks and underground piping.

Typical floor spectra for the containment, turbine/auxiliary buildings and crib house were generated by the A/E as a part of the original design process. In the case of equipment which is not to be reanalyzed, response factors were developed from the original design requirements and the original subsystem and component dynamic analyses.

Capacity factors are derived from several sources of information; plant specific design reports, test reports and generic fragility test data from military test programs. Two failure modes are considered in developing capacity factors for piping and equipment, structural and functional. Equipment design reports delineate stress levels for the specified seismic loading plus normal operating conditions. Where the equipment fails in a a structural mode, (i.e., pressure boundary rupture or loss of support), the median capacity factors and their variability are developed considering the safety factor in the applicable design code, the conservatism in the code specified material strength and energy absorption (ductility). In cases where equipment must function, the capacity factor is derived by comparing the equipment failure (or fragility) level to the design level of seismic loading. Fragility levels are not determinable from qualification test reports but in many cases identical equipment was qualified for much higher earthquake levels which provides guidance on lower bounds of fragility. Also, there are significant amounts of fragility test data on similar generic classes of equipment used in hardened military installations which provide estimates of the fragility level and, thus, the safety factor on the specified design earthquake.

Piping capacities are based on limit moment capacities of pipe fittings. Some limit moment capacities are derived analytically with static test data used as justification for the analytical derivation. For other types of pipe fittings, limit moment capacities are derived by scaling from test data. The derived static load capacities are modified for ductility to reflect the energy absorption capability of piping subjected to dynamic loading.

2.5 FORMULATION USED FOR FRAGILITY CURVES

Seismic induced fragility data are generally unavailable for specific plant components (particularly for the older plants). Thus, fragility curves must be developed primarily from analysis combined heavily with engineering judgment supported by very limited test data. Such fragility curves will contain a great deal of uncertainty and it is imperative that this uncertainty be recognized in all subsequent analyses. Because of this uncertainty, great precision in attempting to define the shape of the fragility curves is unwarranted. Thus, a procedure which requires a minimum amount of information, incorporates uncertainty into the fragility curves and easily enables the use of engineering judgment, was used in this study. The general approach documented in Reference 4 was modified to the SSMRP for specific application and was applied to this study.

The entire fragility curve for any component and its uncertainty can be expressed in terms of the best estimate of the median value of the fragility parameter to which the fragility curve is referenced. For most equipment, the fragility parameter is spectral acceleration but in some cases, zero period acceleration, moments or loads may be specified. For purposes of describing the basis of the fragility curves, acceleration is used as the fragility parameter recognizing that spectral acceleration, S_a, zero period acceleration, ZPA, or some other parameter may be the applicable fragility parameter. The acceleration, A, corresponding to failure is given by:

$$A = \check{A} \, \epsilon_R \epsilon_U \qquad (2\text{-}3)$$

in which ϵ_R and ϵ_U are random variables with unity median representing the inherent randomness (frequency) about the median and the uncertainty (probability) in the median value. Equation 2-3 enables the fragility curve and its uncertainty to be represented as shown in Figure 2-3.

Next, it is assumed that both ϵ_R and ϵ_U are lognormally distributed with logarithmic standard deviation of β_R and β_U, respectively. The advantages of this formulation are:

1. The entire fragility curve and its uncertainty can be expressed by three parameters - $\check{A}$, β_R, and β_U. With the very limited available data on fragility, it is much easier to only have to estimate three parameters rather than the entire shape of the fragility curve and its uncertainty.

2. The formulation in Equation 2-3 and the lognormal distribution are very tractable mathematically.

Another advantage of the lognormal distribution is that it is easy to convert Equation 2-3 to a deterministic composite "best estimate" fragility curve (i.e., one which does not separate out uncertainty from underlying randomness) defined by:

$$A = \check{A}\,\epsilon_C \qquad (2\text{-}4)$$

where β_C is a lognormal random variable with unity median and logarithmic standard deviation β_C given by:

$$\beta_C = \sqrt{\beta_R^2 + \beta_U^2} \qquad (2\text{-}5)$$

This composite fragility curve (shown in Figure 2-3) can be used in preliminary deterministic safety analyses if one only needs a "best estimate" on release frequency and does not desire an estimate of the uncertainty.

The lognormal distribution can be justified as a reasonable distribution since the statistical variation of many material properties (References 5 and 6) and seismic response variables may reasonably be represented by this distribution so long as one is not primarily concerned with the extreme tails of the distribution. In addition, the central limit theorem states that a distribution consisting of products and quotients of distributions of several variables tends to be lognormal even if the individual variable distributions are not lognormal. Use of this distribution for estimating frequencies of failure on the order of one percent or greater is considered to be quite reasonable. Lower frequency estimates which are associated with the extreme tails of distribution must be considered more suspect. However, use of the lognormal distribution for estimating very low failure frequencies of components or structures associated with the tails of the distribution is considered to be conservative since the low probability tails of the lognormal distribution generally extend further from the median than actual structural resistance or response data might extend since such data generally shows cut-off limits beyond which there is essentially zero probability of occurrence.

Characteristics of the lognormal distribution which are useful to keep in mind when generating estimates of $\check{A}$, β_R, and β_U are summarized (References 7 and 8). A random variable x is said to be lognormally distributed if its natural logarithm $\tilde{x}$, given by

$$\tilde{x} = \ln(x), \qquad (2\text{-}6)$$

is normally distributed with the mean of $\tilde{x}$ equal to $\ln \check{x}$ where $\check{x}$ is the median of x, and with the standard deviation of $\tilde{x}$ equal to β which will be defined herein as the logarithmic standard deviation of x. Then, the coefficient of variation, COV, is given by the relationship:

$$COV = \sqrt{\exp(\beta^2) - 1} \qquad (2\text{-}7)$$

For β values less than about 0.5, this equation becomes approximately:

$$COV \approx \beta \qquad (2\text{-}8)$$

and COV and β are often used interchangeably.

For a lognormal distribution, the median value is used as the characteristic parameter of central tendency (50% of the values are above the median value and 50% are below the median value). The logarithmic standard deviation, β, or the coefficient of variation, COV, are used as a measure of the dispersion of the distribution.

The relationship between the median value, $\check{x}$, logarithmic standard deviation, β, and any value x of the random variable can be expressed as:

$$x = \check{x} \cdot \exp(f \cdot \beta) \qquad (2\text{-}9)$$

where f is the standarized Gaussian random variable (mean zero, standard deviation one). Therefore, the probability that x is less than any value x' equals the probability that f is less than f' where:

$$f' = \frac{\ln (x'/\check{x})}{\beta} \qquad (2\text{-}10)$$

Because f is a standarized Gaussian random variable, one can simply enter standardized Gaussian tables to find the probability that f is less than f' which equals the probability that x is less than x'. Using cumulative distribution tables for the standarized Gaussian random variable, it can be shown that $\check{x} \cdot \exp(+\beta)$ of a lognormal distribution corresponds to the 84 percentile value, (i.e., 84 percent of the data fall below the +β value). The $\check{x} \cdot \exp(-\beta)$ value corresponds to the value for which 16 percent of the data fall below.

One implication of the usage of the lognormal distribution is that if a, b, and c are independent lognormally distributed random variables, and if

$$d = \frac{a^r \cdot b^s}{c^t} q \qquad (2\text{-}11)$$

where q, r, s and t are given constants, then d is also a lognormally distributed random variable. Further, the median value of d, denoted by $\check{d}$, and the logarithmic variance β_d^2 , which is the square of the logarithmic standard deviation, β_d, of d, are given by:

$$\check{d} = \frac{\check{a}^r \cdot \check{b}^s}{\check{c}^t} q$$

and

$$\beta_d^2 = r^2\beta_a^2 + s^2\beta_b^2 + t^2\beta_c^2$$

where a, b, and c are the median values, and β_a, β_b, and β_c are the logarithmic standard deviations of a, b, and c, respectively.

The formulation for fragility curves given by Equation 2-3 and shown in Figure 2-3 and the use of the lognormal distribution enables easy development and expression of these curves and their uncertainty. However, expression of uncertainty as shown in Figure 2-3, in which a range of peak accelerations are presented for a given frequency of failure, is not very usable in the systems analyses for frequency of release. For the systems analyses, it is preferable to express uncertainty in terms of a range of failure fractiles (frequencies of failure) for a given acceleration. Conversion from the one description of uncertainty to the other is easily accomplished as illustrated in Figure 2-4 and summarized below.

With perfect knowledge, (i.e., only accounting for the random variability, β_R), the frequency of failure, $p_{f(A)}$, for a given acceleration A can be obtained from:

$$p_{f(A)} = \Phi\left(\frac{\ln(A/\check{A})}{\beta_R}\right) \qquad (2\text{-}12)$$

in which $\Phi(\cdot)$ is the standard Gaussian cumulative function, $\check{A}$ is the "best estimate" of the median acceleration capacity, and β_R is the logarithmic standard deviation associated with the underlying randomness of the capacity. The following simplification in notation will be used:

$$p_f = p_{f(A)}$$
$$p_f' = p_{f(A')}$$
$$p_f'' = p_{f(A'')}$$

i.e., p_f' is the frequency of failure based on the underlying randomness associated with acceleration A, p_f' is the failure frequency associated with acceleration A', etc. Then, with perfect knowledge (no uncertainty inthe frequencies) the acceleration A' corresponding to a given frequency of failure p_f' is given by:

$$A' = \check{A} \exp\left[\beta_R \Phi^{-1}(p_f')\right] \qquad (2\text{-}13)$$

The uncertainty in acceleration capacity corresponding to a given probability of failure as a result of uncertainty of the median capacity can then be expressed by the following probability statement:

$$p\left[A > A'' \mid p_f'\right] = 1-\Phi\left(\frac{\ell n(A''/A)}{\beta_u}\right) \quad (2\text{-}14)$$

in which $P\left[A > A'' | p_f'\right]$ represents the probability that the acceleration A exceeds A" for a given failure frequency p_f'. This probability is shown shaded in Figure 2-4. However, one wishes to transform this probability statement into a statement on the probability that the frequency of failure p_f is less than p_f' for a given acceleration A", or in symbols $p\left[p_f \le p_f' | A''\right]$. This probability is also shown shaded in Figure 2-4. It follows that:

$$p\left[p_f \le p_f' \mid A''\right] = p\left[A > A'' \mid p_f'\right] \quad (2\text{-}15)$$

Thus, from Equations 2-13 and 2-14:

$$P\left[p_f \le p_f' \mid A''\right] = P\left[A > A'' \mid p_f'\right] \quad (2\text{-}16)$$

from which:

$$P\left[p_f > p_f' \mid A''\right] = \Phi\left(\frac{\ell n(A''/\check{A} \exp\left[\beta_R \Phi^{-1} \quad (p_f')\right]}{\beta_u}\right) \quad (2\text{-}17)$$

which is the basic statement expressing the probability that the failure frequency exceeds p_f' for acceleration A", given the "best estimate" of the median acceleration capacity A, and the logarithmic standard deviation β_R and β_U associated with randomness and uncertainty, respectively.

As an example, if:

$$\check{A} = 0.77, \qquad \beta_R = 0.36, \qquad \beta_U = 0.39$$

then from Equation 2-17 for typical values of p_f and A",

$$P\left[p_f > 0.5 \mid A'' = 0.40\right] = 0.05$$

which says that there is a 5 percent probability that the failure frequency exceeds 0.5 for an acceleration of 0.40g.

2.6 COMBINING RESPONSE FACTORS AND FRAGILITY DESCRIPTIONS

The response factor and capacity factor were previously described as being factors of safety relative to the original design analysis. When working with the properties of the lognormal distribution the median fragility level of a component can be expressed as the product of the median response and fragility factors times the original design basis seismic loading.

$$\check{A} = F_R F_C A_{DBE}$$

where $\check{A}$ is the median fragility level of the component, F_R and F_C are response and capacity factors and A_{DBE} is the original seismic design basis loading. The logarithmic standard deviations of the factors may be combined by the square-root-of-the-sum-of-the-squares (SRSS) method.

$$\beta_R = \sqrt{\beta_{R_R}^2 + \beta_{R_C}^2}$$

$$\beta_U = \sqrt{\beta_{U_R}^2 + \beta_{U_C}^2}$$

where β_R and β_U are the logarithmic standard deviations of the fragility description representing randomness and uncertainty and the subscripts, R and C, represent response and capacity.

If no new analyses were being conducted for subsystems, fragility descriptions would conveniently include the response and capacity factors. However, for piping and major NSSS components included in the NSSS system model, new responses will be computed and a probabilitic representation of subsystem response will be available. It is then desirable to provide the fragility descriptions, based on capacity, separately. In cases where the response factors are derived, based upon the original design analyses, they can be easily applied to the fragility in a preprocess program in the manner shown above. Separation of response factors from the fragility description also provides information about the sensitivity of the overall fragility description to response and capacity.

The SSMRP risk model is to have the overall capability of handling many types of probabilistic distributions, including fragility descriptions specified as discrete point by point input. In Phase I however, only normal and lognormal distributions of response and fragility will be utilized. In this report, all subsystem response and fragility descriptions are specified as lognormal distributions. In the event that fragility descriptions, defined as normal distributions, are required, the lognormal distributions, expressed as a median and variance, can be easily converted by a least squares curve fit process. The least squares curve fit should be applied to the range of the fragility curve of most significant interest. The actual fragility curves can be reasonably approximated within plus or minus one standard deviation of the mean or median by many mathematical forms of probabilistic distribution. The difference in the extreme tails for various mathematical distributions will differ significantly, however. The expert opinion questionnaire, Reference 10, requested equipment fragilities at the 10%, 50% and 90% probability of failure levels. A least squares fit of the three points is being used to derive a best estimate normal or lognormal distribution of the questionnaire responses. The same procedure can easily be used to derive a best estimate normal distribution from a lognormal distribution. For a best fit estimate within the plus or minus one standard deviation range, the governing equations are:

$$\mu = \frac{A_{0.16} + A_{0.5} + A_{0.84}}{3}$$

$$\sigma = \frac{A_{0.84} - A_{0.16}}{2}$$

where:

μ = Mean of best estimate normal distribution

$A_{0.16}$ = Acceleration level at 16% frequency of failure corresponding to the minus one logarithmic standard deviation value

$A_{0.5}$ = Acceleration level at 50% frequency of failure corresponding the median value

$A_{0.84}$ = Acceleration level at 84% frequency of failure corresponding to the plus one logarithmic standard deviation value.

σ = standard deviation of the best estimate normal distribution

A normal distribution representation of strength tends to be very conservative in the lower tail of the fragility curve and it is felt that other distributions that tend to truncate the lower tail are more realistic for strength. A strong case for the response distribution is not as evident.

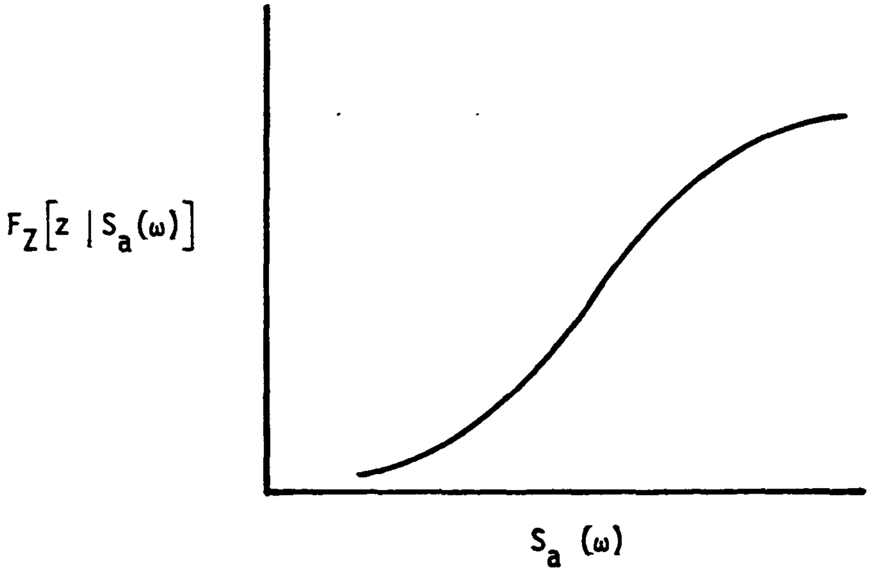


FIGURE 2-1

FRAGILITY CURVE

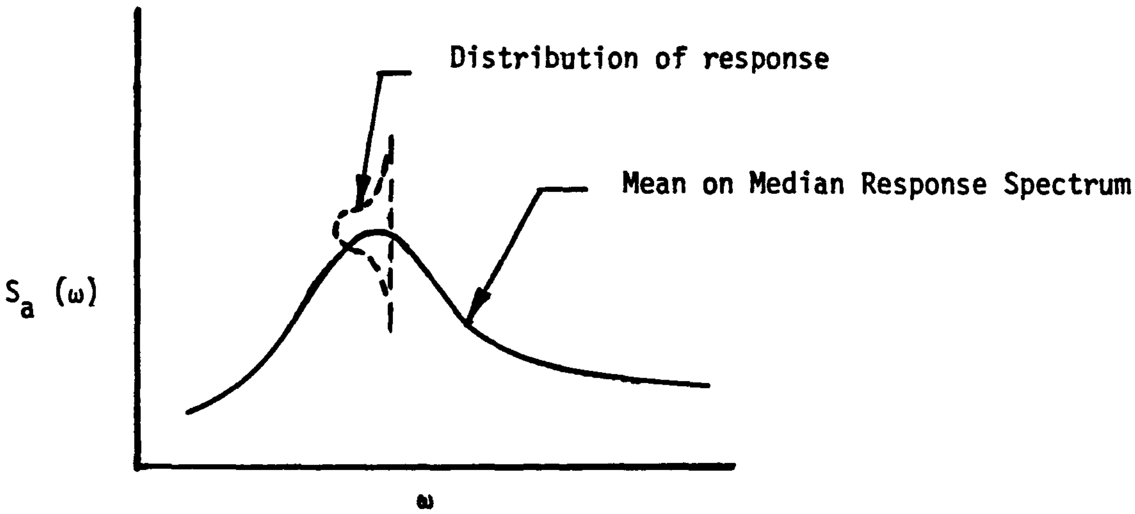


FIGURE 2-2

DISTRIBUTION OF COMPUTED RESPONSE

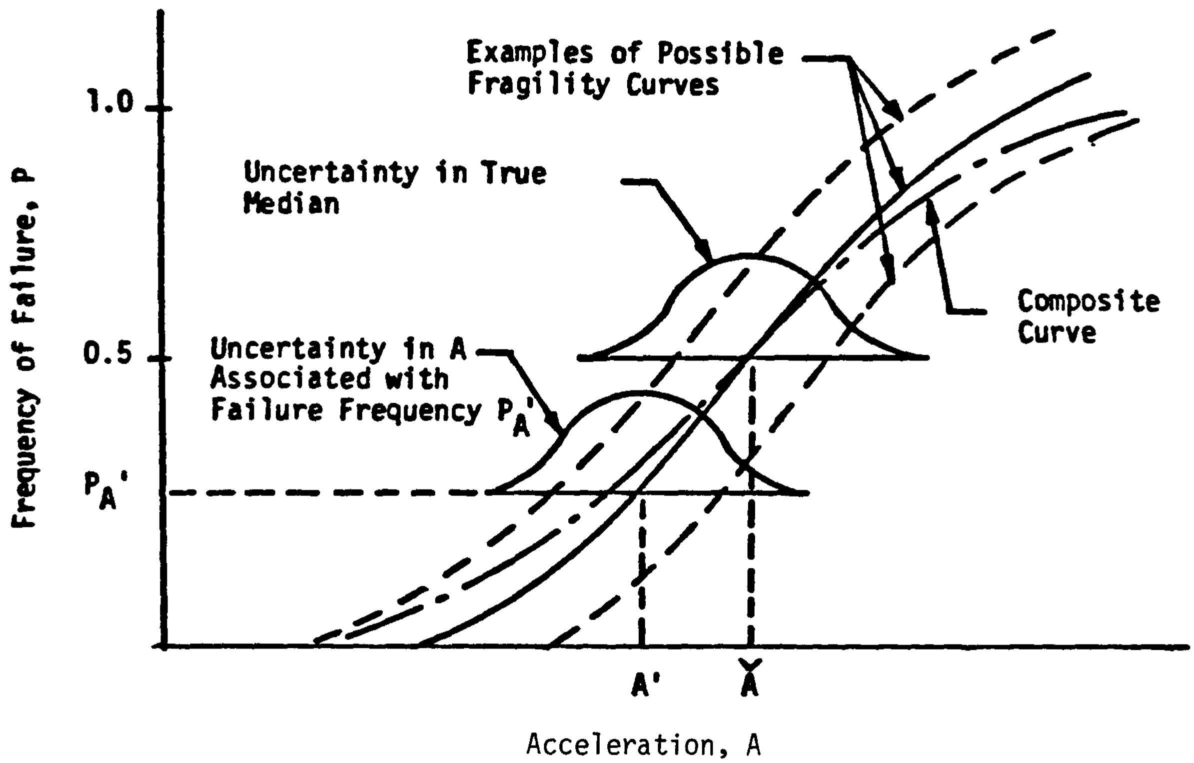


FIGURE 2-3. SIMPLIFIED REPRESENTATION OF FRAGILITY CURVE

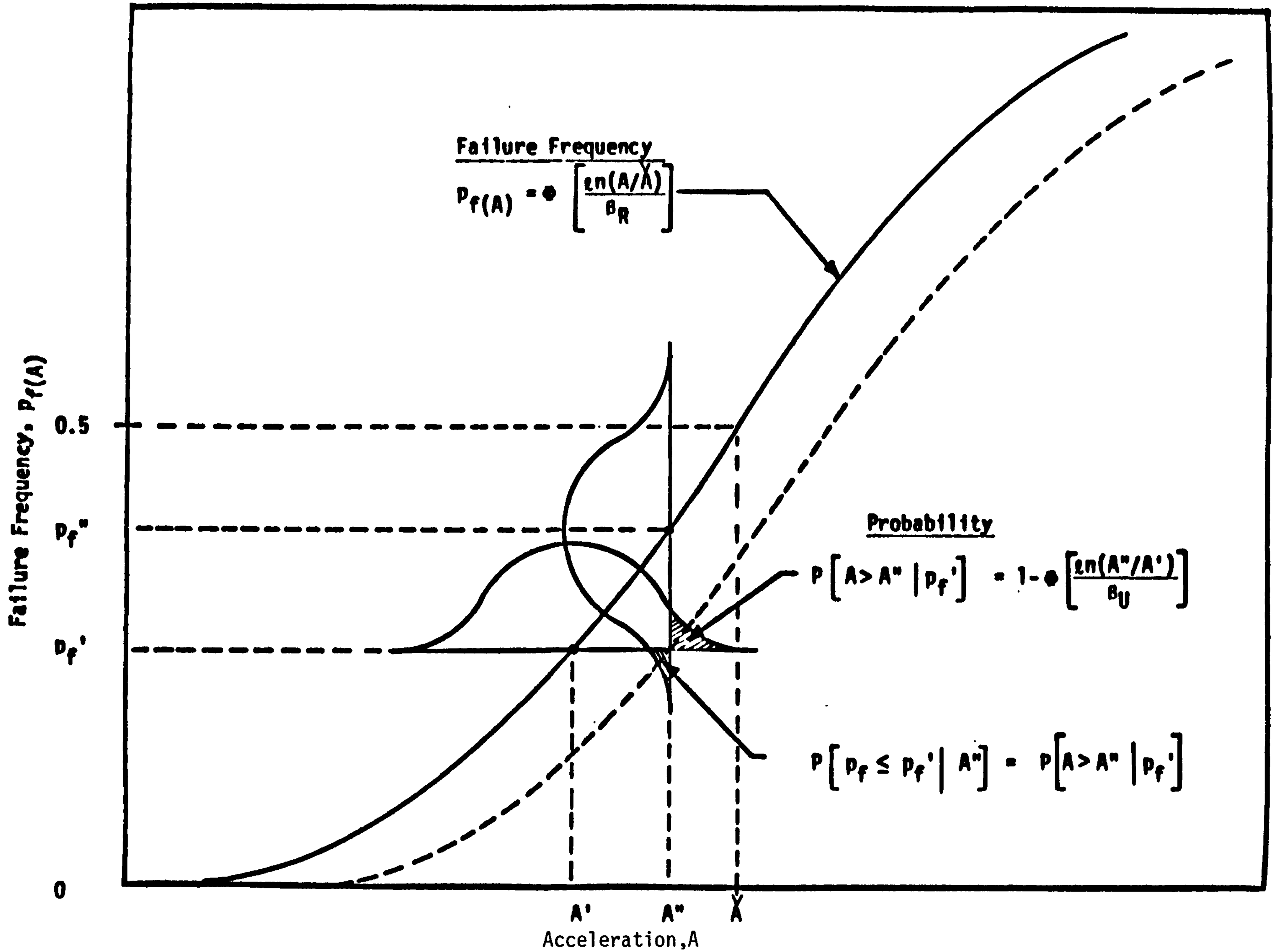


FIGURE 2-4. RELATIONSHIP BETEEN UNCERTAINTY IN ACCELERATION FOR A GIVEN FAILURE FREQUENCY AND UNCERTAINTY IN FAILURE FREQUENCY FOR A GIVEN ACCELERATION

3.0 COMPONENTS AND SUBSYSTEMS TO BE INCLUDED IN THE RISK MODEL

The resources available in Phase I of the SSMRP preclude the inclusion of all safety-related subsystems and components in the risk model. Lawrence Livermore National Laboratory provided SMA with marked-up P&I diagrams depicting the piping systems that will be reanalyzed and included in the risk model. Fragility descriptions for only those piping systems, related components and related instrument, control and electric power systems are included in this study. However, since most of the electric power, instrument and control systems and valves fragility descriptions are generic, virtually all safety-related equipment is included in this study.

The systems specified by Lawrence Livermore National Laboratory for inclusion in the risk model are:

- Auxiliary Feedwater System
- Service Water System
- Residual Heat Removal System
- Nuclear Steam Supply System
- Power Actuated Relief Valve

Only portions of the piping systems are included in the risk model and piping fragility descriptions are limited to those portions to be modeled.

Reference 9, submitted earlier in the program, listed twenty seven generic categories of safety-related equipment. After conducting further research into sources of information on equipment fragility, the number of generic categories were increased to thirty seven. An expert opinion questionnaire, Reference 10, was sent out to recognized experts and manufacturers asking for help in quantifying fragility of nuclear power plant equipment. That questionnaire contained thirty seven generic categories of equipment. Subsequently, a few of the generic categories have been consolidated or eliminated and some added to the extent that there are now thirty five generic categories, for which fragility descriptions are included, in this study. Within a generic category, there may be several plant specific fragility descriptions developed if design information was obtainable. The thirty five generic categories are shown in Table 3-1.

TABLE 3-1

GENERIC FRAGILITY CATEGORIES FOR SSMRP

GENERIC CATEGORY	PLANT SPECIFIC COMPONENTS
1. Reactor Coolant System Class I Vessels and Supports	RPV, Steam Generator, Pressurizer
2. Main Coolant Pumps	
3. NSSS Piping	
4. Large Diameter Piping, 8" and Greater	
5. Intermediate Diameter Piping, 2½"-8"	
6. Large Vertical Vessels and Heat Exchangers with Formed Heads	Accumulator Tanks RHR Heat Exchangers
7. Large Flat Bottom Storage Tanks	Condensate Storage Tank, Diesel Oil Storage Tank. (Square Sided)
8. Large Horiz. Vessels & Heat Exchangers	Pressurizer Relief Tank Component Cooling Water Heat Exchanger
9. Small-Med. Vessels & Heat Exchangers	Boron Injection Tank
10. Buried Pipe	Service Water from Cribhouse & Aux. F.W. from Cond. Storage Tank
11. Large Vert. Centrifugal Pumps with Motor Drive	Service Water Pumps
12. Small-Med. Horiz. & Vert. Motor, Turbine & Diesel Driven Pumps & Compressor	Aux. F.W., Residual Heat Removal, Safety Injection, Diesel Air Starter Comp. Lube Oil, Centrifugal Charging
13. Large Motor Operated Valves 10" and greater	Several Plant Specific Valves; Others are Treated Generically

TABLE 3-1

GENERIC FRAGILITY CATEGORIES FOR SSMRP (Continued)

GENERIC CATEGORY	PLANT SPECIFIC COMPONENTS
14. Large Hyd. & Air Operated Valves	Includes MSIV & Power Actuated Relief Valve
15. Lg. Check, Spring Relief & Manual Valves	
16. Small Motor Operated Valves $<$10"	
17. Small Misc. Valves $\leq$8"	
18. Emergency A.C. Power Units	4160 V Diesel Generators
19. Emergency D.C. Power	Batteries & Racks
20. Switch Gear (Includes Transformer, Breakers & Busses)	4160 V & 480 V
21. Transformer	4160/480 Aux. Transformer, 480/120 to Inst. Bus
22. Instrument Panels & Racks	RPS Nuclear Instrumentation
23. Control Panels & Racks	RPS Process Control
24. Relay Cabinets	RPS
25. Local Instruments	Misc. Pressure & Temperature Sensors
26. Motor Control Centers	All ESF Pumps & Valves
27. Static Inverters	
28. Cable Trays	
29. Breaker Panels	

TABLE 3-1

GENERIC FRAGILITY CATEGORIES FOR SSMRP (Continued)

GENERIC CATEGORY	PLANT SPECIFIC COMPONENTS
30. Air Conditioning & Air Handling Power Units	Containment Fan Coolers
31. Ducting	
32. Control Rods & Drives	
33. Reactor Protection System	
34. Offsite Power	Ceramic Insulators
35. Reactor Internals	

4.0 SUBSYSTEM FRAGILITY

Table 3-1 lists the generic categories of safety-related equipment to be included in the risk model. In this chapter, fragility descriptions for each of the equipment categories in Table 3-1 and many plant specific components are developed utilizing available information provided by the Utility, the Architect Engineer, the NSSS Supplier, and other sources of fragility information.

Fragility levels are expressed as a frequency of failure vs an appropriate fragility parameter and the properties of the lognormal distribution are utilized in describing equipment fragility.

4.1 GENERAL APPROACH AND INFORMATION SOURCES

The general procedure used in deriving fragility descriptions was outlined in Chapter 2.0 wherein a factor of safety and its variability is first developed for equipment capacity, considering strength and, if applicable, the ductility or ability to absorb energy beyond the yield point. The capacity factor is then muliplied by the magnitude of the fragility parameter that was specified for seismic design.

$$\check{A} = F_C A_{DBE} \qquad (4\text{-}1)$$

where $\check{A}$ is the median capacity expressed in terms of the fragility parameter, i.e., acceleration, force, moment, etc., F_C is the capacity factor and A_{DBE} is the magnitude of the fragility parameter specified for seismic design.

In general, no new analyses were conducted on equipment items. Where available, original design analysis were used. In cases where design analysis results were not readily available, capacities were treated generically using generic analyses and limited test results from several sources or, in a few instances, new analyses were conducted.

4.1.1 Information Sources for Equipment

Several sources of information were used to derive plant specific and generic fragilities for equipment. These sources incude:

a. Design reports for plant specific equipment.

b. Final Safety Analysis Report.

c. High Seismic Zone Qualification Reports for identical and similar equipment.

d. United States Corps of Engineers Shock Test Reports.

e. Specifications for seismic design of equipment.

f. Test Reports for Qualification of Zion Equipment.

g. Topical Reports.

Several design reports were made available to the Lawrence Livermore National Laboratory for plant specific equipment through Commonwealth Edison and their Architect Engineer and NSSS supplier. For the most part, the design reports for major NSSS items were based on reference design spectra more severe than the Zion spectra and were complete engineering reports that both summarized and provided details of analyses for seismic qualification. Most design reports for non NSSS items were based on Zion specific seismic conditions. Many of these reports did not have summaries and the calculations were difficult to follow such that it was very difficult to use all of the information available. This was typical of valve reports and, as such, most valves are treated generically based on a distribution of capacities obtained from a limited number of design reports and qualification test reports.

The Final Safety Analyses Report, Reference 3, provided general seismic design criteria and in some instances, summaries of critical stresses, qualification results, etc.

In the case of the reactor protection system electrical and electronic equipment, Westinghouse provided a series of WCAP reports (Refs. 11 and 12) that documented high seismic zone qualification tests on similar or identical equipment to that in the Zion nuclear power plant. The high seismic zone qualification test environment exceeded the Zion seismic environment by a large margin.

Fragility tests and severe shock environment tests have been conducted for off-the-shelf-type equipment similar to electro-mechanical, electrical and control equipment that was installed in nuclear power plants of Zion vintage. The results of some 60 test programs are summarized in Reference 13. Information from these shock test reports was used in deriving generic capacities of equipment where plant specific information was not readily available.

Generic specifications for seismic qualification of equipment were provided to the SSMRP by Sargent and Lundy. In cases where plant specific qualificaiton reports were not readily available, knowledge of the vendor requirements plus generic fragility and qualification test data were combined to develop fragility descriptions.

Very few qualification reports were obtained for equipment qualified by testing. In those few instances where test reports were provided, it was difficult to determine the test input and resulting spectrum. Consequently, most equipment qualified by test was treated generically.

Several reports summarizing equipment damage during major earthquakes were reviewed, References 14 through 25. Most reports do not provide sufficient information to determine the extent of the loading experienced by equipment during the seismic event. Reference 25 does, however, provide such information and indicates that only insignificant failures were present for equipment that experienced from 0.5 to 1.8 g's spectral acceleration, although most equipment was rigid and experienced less than 1g spectral acceleration. This information is comforting in that steam plant power mechanical, electrical and control equipment have been demonstrated to withstand an earthquake of 2 to 3 times the Zion design basis earthquake, but, since no significant damage was observed on equipment typical of nuclear power plant equipment, fragility descriptions cannot be concluded from the information.

No attempt was made to examine Navy shock test data or shock and vibration data for airborne equipment as these items are usually special designs qualified for marine or airborne use and the typical shock or vibration input is not typical of seismically induced input.

The above sources of information were applied to different equipment items, as appropriate, in the development of plant specific and generic fragility descriptions.

4.1.2 Equipment Categories

Because of the variety of equipment to be included in the risk model, the variety of failure modes and the various sources of fragility information available, it is necessary to divide the equipment items into distinct groups. Ideally, if complete design reports and fragility test reports were available, all equipment items would be treated individually. This is not the case and it is necessary to treat some groups of equipment generically. The selected major categories of equipment fragility are:

a. Piping to be reanalyzed by Lawrence Livermore Laboratory.

b. Plant specific equipment whose fragility descriptions are based on structural failure and for which design reports or summaries of design reports were available.

c. Plant specific equipment whose fragility descriptions are based on functional limits and for which design reports or summaries of design reports were available.

d. Generic structural capacities of equipment derived from knowledge of the design specifications and the strength factors of safety inherent in the governing codes and standards.

e. Piping support fragilities derived from the strength factors of safety inherent in the governing design codes.

f. Generic structural and functional capacities of equipment derived from high seismic zone qualification test data.

g. Generic structural and functional capacities of equipment derived from military shock test data and various seismic qualification test reports.

4.2 DEVELOPMENT OF LOAD SCALE FACTORS FOR PIPING ELEMENTS

In developing fault trees for SEISIM, the individual safety related piping systems will be modeled but not the individual piping elements or supports. It is desired that only one fragility description be input into SEISIM to describe the fragility of all pipe elements and systems. This can be accomplished by relating individual pipe element fragilities to a master pipe element fragility via a load scale factor, F_p, where the load scale factor is defined as:

$$F_p = \frac{\text{Capacity of Reference Pipe Element}}{\text{Capacity of Pipe Element Under Consideration}}$$

In the SSMRP, several piping systems will be analyzed for seismic response to varying level earthquakes represented by multiple time histories for each given level. Internal moments will be calculated for these systems at all piping model node points. In order to define the frequency of failure of a piping system, the most critical elements of the system must first be identified by comparing the calculated internal moments to the fragility relationships of the pipe elements under consideration. This process would entail the development of a fragility curve for every pipe fitting type, pipe size, schedule, material and operating temperature characteristic of the safety related piping. However, by using a load scale factor approach the calculated internal moments at each piping node can be scaled for comparison to a single master or reference fragility curve. The quantification of scale factors requires the development of individual pipe element capacities for all element types, sizes, schedules, materials and temperature but this can be accomplished outside of the risk analysis program, greatly simplifying the risk analysis process and reducing voluminous computer calculations. All screening of critical pipe elements and selection of the critical element or elements that govern the piping system fragility can be accomplished in a preprocessor.

The component fragility project is charged with developing the load scale factors. This task entails the establishment of the piping element types, sizes, schedules, materials and temperaures, establishment of a rational pipe element failure criterion, development of static load capacities of all applicable pipe fittings and modifications of the static capacities to account for the energy absorption capability of piping when subjected to vibratory dynamic loading.

4.2.1 Establishment of Applicable Pipe Elements

P & I diagrams of safety related piping systems, for which LLL plans to conduct dynamic analyses, were provided to SMA. The P & I diagrams define the pipe sizes and index designations which can be utilized, via Reference 26, to establish the piping materials, schedules and design temperatures. In most cases actual normal operating temperatures could not be defined and the design temperatures, which envelop all normal operating conditions, had to be used.

The piping systems to be modeled in the SSMRP are:

Primary coolent piping including branch lines to the pressurizing and accumulator.

Residual heat removal system (Partial)

Service Water System (Partial)

Auxiliary Feed Water System (Partial)

Centrifugal Charging System (Partial)

Pipe sizes within these systems range from 3 inches to 48 inches. Materials of construction are various grades of austenitic stainless steel and low carbon steel. Design and operating temperatures range from ambient to 595 degrees Fahrenheit.

SMA did not review piping layout and isometric drawings to determine the exact types of pipe fittings for each piping system. Instead, fitting types were identified through other sources. Branch sizes, but not the type, and reducers are denoted on the P & I's. Virtually all piping systems contain straight pipe, buttwelds and elbows or bends,the bend radaii could not, however, be identified. Some miter joints are known to exist in large diameter, thin wall low pressure piping.

Lacking complete detail on all fittings, it was decided to be more efficient to provide scale factors to LLL to cover all possible combinations rather than review detailed drawings. The fittings types for which scale factors are provided are:

Straight Pipe (No Welds)
Butt Welds
Long Radius Elbows (1 1/2 D bend radius)
Short Radius Elbows (1D bend radius)
ANSI B 16.9 Butt Welding Tees
Fabricated, Reinforced Branches

Fabricated Unreinforced Branches
Reducers
Miter Joints
Pipe Bends ($R \geq 3D$)

Socket welds were not used on any of the piping systems being modeled and are consequently not included. Taper transition joints strengths are assumed to be governed by butt weld joint strengths, thus are implicitly covered.

4.2.2 Pipe Element Failure Mode

In order to develop relative capacities of pipe fittings of all sizes and materials it is necessary to relate to a reference failure capacity and to have a rational means of scaling from the reference. The reference capacity must also be based upon a rational failure mode. In attacking this problem the considerations are: possible failure modes, available information on pipe fitting capacities and the monetary resources available.

Three failure modes were considered:

1) Plastic Collapse
2) Low Cycle Fatigue (ASME approach)
3) Crack Growth and Fracture

Plastic collapse of a fitting does not necessarily result in failure since more than one hinge must form in a beam system for system collapse. Plastic collapse could be considered a lower threshold of piping system failure.

Low cycle fatigue, as applied by the ASME code, was considered. In this consideration, the ASME code fatigue curve for carbon steel was adjusted to remove the code safety factor of 2 on stress range or 20 on cycles. Assuming 10 cycles of a strong motion earthquake, the strain range associated with failure would be on the order of 12% or ± 6% alternating strain. One would not expect a fatigue type failure from an earthquake to govern unless a significant portion of the fatigue life had been used up prior to the occurrence of the earthquake or a large manufacturing flaw existed. The code approach to fatigue failure is one of significant crack initition, not necessarily fracture or even propagation to the extent of a leak. Consequently, prediction of fatigue failure via the ASME code process is considered to be a lower threshold of failure.

Crack growth and fracture for any but simple geometries would be extremely difficult to apply within the resources of the SSMRP Fragility Project. The ASME code method provided in Section XI, Ref. 27, is applicable to sections 4" and greater in thickness, limited to carbon steel and covers only two geometries. An approach used in the Diablo Canyon risk study, Ref 28, assumed crack growth and fracture failures only in butt welded pipe joints and neglected all other types of fittings. Butt welds tend to have the least margin of safety when comparing static collapse moment to code allowable moment, Ref 29, and this approach may have been rational for the scope of the Diablo Canyon Study but is not compatible with the goals of the SSMRP.

While crack growth and fracture is certainly a more desirable approach, the generation of the required information for hundreds of fitting sizes, geometries and materials is not feasible in the SSMRP. The USNRC Sponsered Load Combination Program is studying probabilistic fracture mechanics and information from that program could be useful for the primary coolant system fragility description but was not available in the time frame of Phase 1 of the SSMRP.

Considerable static collapse data exist for piping elements and some simple piping systems, Refs. 30-46; thus, a good data base exists for the collapse type of failure mode. Some limited fatigue testing of piping elbows is reported in Ref. 31; however, that reference, in itself, is not sufficient information to develop seismic fragility descriptions for all types of pipe elements.

A choice was made to develop piping fragility descriptions based on pipe element collapse. This mechanism of failure has the largest data base and is the easiest method to apply.

4.2.3 General Approach

Figures 4-1 is a flow diagram that displays a process for developing the load scale factors using plastic collapse as the governing failure mode. The process first involves the development of static capacities of pipe elements of all sizes, shapes and materials applicable to ZION safety systems. The static capacities are then modified upward to reflect the energy absorption capability during dynamic seismic loading events. The dynamic capacities are then compared to the reference dynamic capacity to develop scale factors, F_p's, where

$$F_p = \frac{\text{Dynamic Capacity of Fragility Curve Reference Element}}{\text{Dynamic Capacity of Piping Element Under Consideration}}$$

The reference static capacities are based on collapse moments for fittings as determined from tests or by plastic analysis. Data are available for some sizes of straight pipe, ANSI B16.9 elbows, tees and fabricated branch connections. These static capacities are modified to reflect the energy absorption capability inherent in structures when loaded dynamically and analyzed on a linear elastic basis. The method proposed by Newmark, as further expanded in Ref. 47, was used. In this method, a dynamic capacity factor, F_μ, which is a function of the component or structural system ductility, is developed. For systems, such as piping, that respond in the amplified acceleration range of the response spectrum, the dynamic capacity factor can be approximated as:

$$F = \sqrt{2\mu-1} \qquad (4-2)$$

where μ is the ductility ratio, i.e., the ratio of deformation at failure in an equivalent elasto-plastic system to the elastic deformation at the failure load. The dynamic capacity factor, F_μ, is multiplied times the static capacity to develop a dynamic capacity referenced to an elastically computed response.

In order to scale static capacities from test data, ASME code stress intensification factors were used. Much work has gone into the development of stress indices and stress intensification factors for the ASME code. These factors, along with pipe fitting section properties and material properties, reflect the relative load carrying ability of pipe fittings and can be used to scale capacities from a reference capacity determined by test. Figure 4-2 shows how this was accomplished.

Stress intensification factors were chosen for purposes of scaling rather than Class 1 stress indices. Either intensification factors or indices are considered equally valid for purposes of scaling as long as they are used consistently. Intensification factors were chosen primarily due to the fact that Class 1 stress indices do not exist for all fitting types used in the design of safety related ZION piping, i.e., miter bends. Also, the original designs were based upon using ANSI B31.1 stress intensification factors rather than ASME code Class 1 stress indices.

A material correction factor, F_M, was used for elbows based on differences in collapse test capacity observed for elbows constructed of low carbon steel and austenitic stainless steel. The material correction factors, based upon collapse tests, do not correlate directly to specified yield strength, as material strain hardening characteristics enter into the collapse mechanism. Since the measured yield strengths varied for different test items, the measured collapse capacities were normalized to code specified minimum yield strengths to develop material factors for carbon vs stainless steel.

Temperature correction factors, F_T, were developed by comparing the specified yield strength at the design temperatures of the fittings under consideration to the specified yield strengths of the fitting material at room temperature.

4.2.4 Capacity of Reference Pipe Elements

A 6 inch Schedule 160 carbon steel butt weld pipe joint was selected as the basis for the master fragility relationship. Base material was considered to be A-106 B at room temperature with a code specified yield strength of 35 ksi and a specified ultimate strength of 60 ksi. The specified strengths are considered to be 95% non-exceedance values corresponding to 1.65 standard deviations below the average strengths. Average stength is not specified in the ASME code but is typically about 25% above the specified value, Ref. 48.

Material strength distributions are typically skewed such that a lognormal representation of material strength is considered to be a reasonable representation. For instance, Ref. 29 reports that the yield strength of AISI type 304 stainless steel can vary from 25 to 69 ksi. The code specified value is 30 ksi and the average yield strength is, per Ref. 48, about 1.25 times the specified value. Assuming a lognormal distribution, the logarithmic standard deviation is about 0.14.

In developing the range of strength for the reference pipe element an analytical limit type analysis procedure was utilized to develop upper and lower values of moment capacities accounting for strain hardening affects and accounting for a low probability that a large flaw could exist.

The upper value of moment capacity was developed based upon a procedure in the ZION FSAR ammedements, Q 4-45-3, wherein the limit moment capacity is derived from integration of the stress field over the pipe cross section and assuming the outer fibers to be at the material ultimate strength with the neutral axis at the material yield stength. The derived upper value limit moment capacity is 1.65×10^6 in-lbs. This value is considered to be approximately one logarithmic standard deviation above the median.

A lower bound capacity was derived via a limit analyses procedure documented in Appendix B of Ref. 49. A through wall eliptical flaw of length equal to six times the wall thickness was assumed. A new neutral axis was derived for the flawed pipe and the limit moment was calculated assuming an elastic-perfectly plastic model with a flow stress equal to a specified fraction of the sum of the yield and ultimate strengths. The derived lower bound moment capacity was 9.5×10^5 in-lbs. Since the existance of a flaw of the size assumed has a very low probability of occurance, the lower value is considered to be a minus 3 logarithmic standard deviation value. This correspondends to about a 10^{-3} probability of occurance.

With the establishment of the upper and lower bound values, and assuming the properties of the lognormal distribution, the medium moment capacity for static loading was computed to be 1.41×10^6 in-lbs. Combining the variance of the strength due to the failure model with the variance of the material properties, the logrithmic standard deviation on strength is computed to be 0.22. The random portion of this is due to random variation in material properties and is considered to be approximately 0.1 with the uncertainty equal to 0.20.

The static capacity was then modified for ductility. For heavy wall steel piping elements loaded primarily in bending, the ductility is considered to range from 1.0 to 5, where the low value of 1.0 represents reduced ductility for the flawed condition. A ductility of 5 corresponds to about 1% primary strain observed at instability from Ref. 46 in limit moment tests of some piping fittings. The associated ductility factors from Equations 4-2 are 1.0 and 3.0. Asuming these factors to represent approximately a plus or minus two logarithmic standard deviation range the median ductility factor was computed to be 1.73 with the logarithmic standard deviation equal to 0.27. The random portion is due to the randomness of the material and weld joint ductility and is considered to be approximately 0.15 with the uncertainty equal to 0.22. In addition, there is a dispersion on this ductility factor due to the uncertainty in the use of Equation 4-2. The coefficient of variation, approximate logarithmic standard deviation, is estimated to be approximately 0.15 which is considered to be all uncertainty.

The median capacity of the reference pipe element, modified for ductility, is the ductility factor times the median static capacity or:

$$M = 2.44 \times 10^6 \text{ in-lbs}$$

The overall variabilities, expressed as logarithmic standard deviations representing randomness and uncertainty, are obtained from the square root of the sum of the squares of the variabilities on individual variables contributing to the overall capacity.

$$\beta_R = 0.18$$

$$\beta_U = 0.33$$

4.2.5 Static Capacities of Pipe Elements

Static capacities of all types and sizes of pipe elements are derived primarily by scaling limited test data on pipe elements to other sizes, materials and temperatures via the use of stress intensification factors and material yield strengths as specified in the ASME Code. Figure 4-2 summarizes the derivation of static capacities of pipe elements by scaling from a reference capacity where the reference capacity may be derived either analytically or experimentally.

4.2.5.1 Straight Pipe

The static capacity of straight pipe was derived analytically as:

$$\check{M} = \check{K} \, Z \, S_y \quad \text{where}$$

$\check{M}$ is the median collapse moment, $\check{K}$ is a plastic bending shape factor, Z is the pipe section modulus and S_y is the median material yield strength at the specified design or operating temperature. The theoretical shape factor for thin wall pipe and an elastic, perfectly plastic material model is $4/\pi$ or about 1.27. For thicker wall pipes and strain hardening material models, the effective shape factor increases.

Test data from References 33, 34, 36, 38, 39, 40 and 44 indicate that effective shape factors range from 1.4 to greater than 2.8 depending upon the D/t ratio, material, strain hardening exponent and definition of collapse.

For most of the data, the effective shape factor at instability ranged from 1.4 to 1.67 for D/t less than or equal to 50 with 1.5 being a representative value. The D/t range covers all piping of Schedule 40 or greater in thickness.

For comparison, the effective shape factor for the reference pipe element is 1.8 as this is a very heavy wall pipe of D/t equal to about 8.23. A shape factor of 1.5 was chosen to represent a median value for the variety of piping used in the Zion nuclear power plant. Median yield strength, S_y, was estimated by taking 1.25 times the code specified yield strength at temperature.

4.2.5.2 Butt Welds

Butt weld capacities are also derived via limit analysis, considering reduced strain limits as compared to straight pipe. For a sample experimental stress strain relationships and a typical schedule 80 pipe geometry, a shape factor of 1.5 corresponds to a ductility of about 5.0 which was used as a median value for deriving the median dynamic capacity of straight pipe. For butt welds the strain limit was reduced to one half of that for straight pipe, i.e. a median ductility ratio of 2.5 was used. Reducing the strain limit by factors of 2.0 has a small effect on static capacity. Using a simple expermential stress strain relationship, the static capacity of butt welds was computed to be about 93% of the static capacity of straight pipe. The 93% factor was used to derive butt weld static capacities.

4.2.5.3 Elbows

Reference 46 summarizes the results of static collapse tests conducted on schedule 40 and 80 long and short radius elbows constructed of carbon and stainless steel. The static capacities of carbon steel elbows were derived from the relationships:

$$M_c = \frac{M_{ref}\ i_{ref}\ Z_c\ F_M\ F_T}{Z_{ref}\ i_c} \qquad (4\text{-}3)$$

where M_{ref} is the experimental static capacity of a 6" Sch. 80 long radius carbon steel elbow at room temperature, i is the ASME code stress intensification factor for Class 2 and 3 piping, Z_{ref} is the section modulus of the reference fitting, Z_c and i_c are the section modulus and stress intensification factor of the component under consideration and F_M and F_T are material and temperature correction factors. The product of $F_M F_T$ is equal to the code specified yield at temperature, for the component under consideration, divided by the code specified yield of the reference fitting at room temperature.

The experimental data from Reference 46 indicate that stainless steel elbows have a lower limit moment capacity than carbon steel elbows when experimental capacities are adjusted to the same yield strength. This is apparently due to the strain hardening characteristics of the materials. If the capacities are adjusted by ratioing the tested fitting yield strength to code specified yield strength, the limit moment capacities of stainless steel elbows are about 75% of the carbon steel elbows. Hence, for convience, the room temperature static capacities of stainless steel elbows were taken as 75% of the room temperature capacities of carbon steel elbows of the same geometry. Capacities were then adjusted for elevated temperature by comparing the specified yield at elevated temperature to that at room temperture.

The experimental data of Reference 46 indicate that the static limit moment capacities of short radius elbows are slightly greater than those of long radius elbows even though the stress intensification factors are greater. The stress intensification factor is a much better correlation to fatigue life (localize stress-strain dependent failure) rather than to limit load. Since there is little difference in the static capacities of long and short radius elbows the scale factors derived for long radius elbows are considered to be applicable to short radius elbows as well.

Pipe bends, typically with bend radaii equal to three to five times the nominal pipe diameters, were not included in any of the test data examined. Bends have stress intensification factors much less than standard long radius elbows. It is estimated that bends would have dynamic load capacities between those of straight pipe and butt welds; thus, butt weld load factors are considered to govern for bends, since most bends terminate in a butt weld.

In a few instances, for small diameter heavy wall elbows, the derived load scale factors, F_p, are greater for butt welds than for elbows. This is due to the greater ductility assigned to elbows than to butt welds and the fact that heavy wall small diameter elbows have stress intensification factors nearly equal to 1.0, implying static strength equivalent to straight pipe. Fatigue test data for elbows, reported in Reference 31, indicate that initial fatigue cracking often occurs in the butt weld joint and not in the fitting. Therefore, for those cases in Table 4-1, where F_p factors are greater for butt welds than for elbows, the butt weld factor should govern.

4.2.5.4 Reinforced Branch Connections and Tees.

Reinforced carbon steel branch connections and tees, of the fabricated or integrally forged type, appear from the test data of Refs. 30 and 31, to have capacities greater than the branch pipes. Therefore, for reinforced carbon steel tees and branches, the butt weld capacities of the run or branch will be the governing criteria.

Very little data exist for reinforced stainless steel branches. The very limited data from Reference 31 indicate that the limit moment, for fabricated reinforced stainless steel branches, is about equal to the branch pipe yield strength. The tests were conducted, however, with a pressure induced hoop stress nearly equal to the yield strength of the material. Furthermore, the definition of collapse used by the experimentors is that of the ASME code, Appendix II, Reference 50, which conservatively corresponds to a total deformation of only about two times the linear deformation. There were no test data reviewed for reinforced stainless steel branches with lower or zero pressure stresses. Test data on unreinforced branches of similar geometry, and with a pressure induced hoop stress near yield, indicated moment capacities only slightly lower. It appears that the high pressure stress had a dominant effect on the collapse capacity of the fittings tested as the pressure stress used in the experiments was about 0.9 times the minimum code specified yield strength. At elevated temperatures, 0.9 times the yield strength is one of the governing criteria for specifying code allowables, but, at room temperature, the temperature of the tests, the allowable stress is 2/3 of the yield and the applied pressure stress was 37% above the code allowable. The tests were, therefore, not representative of actual plant operating conditions and the definition of collapse was more conservatively defined than expected deformations at complete pipe system failure. Consequently, it is concluded that, for branch connections meeting code allowable pressure stress limits, the moment capacities of reinforced stainless steel branches are approximately equivalent to the capacities of the branch pipe butt welds.

No data exist for loading of the run. It is expected that, for reinforced branch connections, the run capacity of the fitting would be equivalent to the run pipe butt weld capacity.

No data were uncovered for integrally reinforced stainless steel tees corresponding to ANSI B16.9. It is therefore assumed that their capacities are equal to the capacities derived for fabricated reinforced branches.

In summary, the static limit moment capacities of reinforced branch connections are equal to the static limit moment capacities of the connecting branch and run pipe butt weld joints.

4.2.5.5 <u>Unreinforced Branch Connections</u>

Considerable test data exist for static limit moment capacities of unreinforced branch connections, most of which are summarized in Ref. 29. In all cases the limit moments of the unreinforced branches are less than the limit moments of the connecting pipe for both carbon steel and stainless steel fittings. It was therefore elected to develop capacities of unreinforced branches in the same manner as for elbows. That is, to scale the capacities, via Equation 4-3, from a reference limit moment capacity using stress intensification factors.

$$M_c = \frac{M_{ref}\ i_{ref}\ Z_c\ F_M\ F_T}{Z_{ref}\ i_c} \qquad (4\text{-}3)$$

In this case the reference branch connection is constructed of carbon steel with parameters:

$D = 5.789"$	$d = 3.762$
$T = 0.187"$	$t = 0.124$
$i = 5.47$	$Z_{br} = 2.079$
	$Z_{run} = 4.922$

M_{ref} is the average collapse load capacity from the test data accounting for the average yield properties. Collapse is determined from the load-deflection diagram to be the point of plastic instability, which is about 10% higher than the ASME code definitions of limit moment capacity. Other terminology is as defined previously.

Unlike the situation with elbows, the limited test data for stainless steel unreinforced branches do not indicate an appreciable difference between stainless steel and carbon steel fittings when capacities are normalized to the same yield strength. Therefore, the above criterion is used without modifications for all materials of construction.

There are a few exceptions to the above criteria for the case of a heavy wall run with a small diameter branch. If the calculated component capacity for the run or branch is greater than the capacity of the corresponding butt weld, then the butt weld capacity governs. Also, in the case of the run, with a run to branch diameter ratio greater than 3, the run butt weld is considered to be governing.

4.2.5.6 Miter Joints

There were no test data available for miter joints. Miter joints deform much in the same manner as elbows and probably have static limit moment capacities similar to elbows of equal size. Miter joint stress intensification factors are greater than for elbows of equivalent dimensions. Stress intensification factors are a better indication of fatigue strength reduction than limit moment reductions but, lacking static test data on miter joints, it was elected to scale miter joint capacities in the same manner as for elbows, using as a reference, the 6" Schedule 80 long radius carbon steel elbow, the same reference fitting used for scaling elbow capacities.

4.2.6 Ductilities of Pipe Elements

The carbon and stainless steel materials from which piping are constructed are very ductile in themselves. However, if stress-strain and moment rotation relationships are examined for the test data, the ductility at instability is not necessarily as high. A review of the strain gage data from Ref. 46 indicated that the strain at instability of elbows was about 1%, corresponding to a ductility of about 5. From the tests of ANSI B16.9 tees, reported in Ref. 30, it was observed that failure was ductile fracture of the branch pipe to tee weld joint in the heat affected zone rather than collapse of the fitting. Examination of the moment rotation diagrams from all tests indicates a ductility of 2.1 to 2.75 with an average of about 2.3.

It was indicated previously, in deriving limit moment capacities for straight pipe and butt welds, that a lower strain limit value would be considered for butt welds than for straight pipe. This assumption is consistent with the observed differences in ductility stated above for forged elbows and butt welds on a branch pipe. There were no dynamic test data available to support the selection of ductilities for piping elements, consequently the ductilities were selected based on observed stress-strain and moment rotation relationships at static instability. The following ductilities and associated ductility factors were selected.

Element	Ductility	Ductility Factor $F_\mu = \sqrt{2\mu-1}$
Straight pipe	5.0	3
Butt welds	2.5	2
Elbows	5.0	3
Miter joints	2.5	2
Branch connections	2.5	2

4.2.7 Load Scale Factors

The static load capacities derived for each pipe element were multiplied by the ductility factors to result in a dynamic load capacity for comparison to the reference dynamic load capacity. The load scale factors, F_p, described as:

$$F_p = \frac{\text{Capacity of Reference Pipe Element}}{\text{Capacity of Pipe Element Under Consideration}} \qquad (4\text{-}4)$$

were then derived for all pipe element types, materials and temperatures defined for the risk model. Table 4-1 summarizes the resulting load scale factors.

4.3 EQUIPMENT CAPACITY FACTORS

In this section, capacity factors are derived for plant specific and generic equipment items listed in Table 3-1.

4.3.1 Plant Specific Structural Capacities Derived from Design Reports

Major equipment items related to safety, which fail in a structural mode, are derived in this section. Since the equipment fails in a structural mode, both a strength factor, F_S, based on static strength, and a ductility factor, F_μ, based on inelastic energy absorption, are considered. The capacity factor is then the product of the strength and ductility factors. In the case of metal structure, the ultimate load capacity under static load is defined as the limit load or stress, i.e., that load or stress at which the displacement increases without bound for a small additional increase in loading. Since the interest is in median centered capacity, design allowable values or lower bound loads such as the ASME code stress allowables, Reference 50, the ASME Code Appendix II definition of plastic collapse, or analytically derived lower bound limit load capacities are not used. The ASME code allowable stresses have significant margins against structural failure. The ASME Appendix II definition of plastic collapse corresponds to a ductility of less than 2.0 and the analytically derived classic lower bound limit moments are based upon minimum properties and elastic perfectly-plastic material behavior. In deriving median capacities, concerted effort was made to be realistic about capacities and, as such, average material properties were used and larger deformation capability and strain hardening, where feasible, were considered in order to best estimate the median capacity of structural elements.

Depending upon the mode of failure and geometry, i.e., bending, tension, buckling, etc., the ductilities are adjusted accordingly. In order to quantify the variability in capacity due to both randomness in strength and ductility and uncertainty in the median of each variable, realistic estimates were made on upper and lower bounds of strength and ductility.

Capacities for components in this classification are derived from the following relationships:

$$F_C = F_S F_\mu \qquad (4\text{-}5)$$

where F_S is the strength factor of safety and F_μ is the ductility factor.

The strength factor, F_S is derived from the equation:

$$F_S = \frac{\dfrac{P_C}{P_D} - \dfrac{P_N}{P_D}}{\dfrac{P_T}{P_D} - \dfrac{P_N}{P_D}} \qquad (4\text{-}6)$$

where P_C is the median collapse load or stress, P_N is the normal operating load or stress, P_T is the total normal plus seismic load or stress and P_D is the code design allowable load or stress.

In many instances, design reports provided the exact values for use in Equation 4-6. Some variability is assigned to each value in the above equation to account for the range of material properties and the uncertainty in actual loading.

The logarithmic standard deviations on strength, β_{R_S} and β_{U_S}, are derived considering the random and uncertainty variability of each of the variables making up the strength factor.

For structures that respond in the amplified response region of the design spectrum, the ductility factor, F_μ, introduced in Section 4.1, is:

$$F_\mu = \varepsilon\sqrt{2\mu - 1} \qquad (4\text{-}7)$$

where μ is the ductility and ε is a variable of median equal to unity with a logarithmic standard deviation of about 0.15 to 0.2, which represents the uncertainty in the use of Equation 4-7. For equipment that is considered rigid, the ductility factor is 1.0; i.e., the earthquake loading behaves the same as a static load and no credit can be taken for inelastic energy absorption.

Due to the large number of components, not all derivations are reported in detail. Major components of the NSSS system are included to portray the procedure. Fragility descriptions for other safety-related equipment were developed in a similar manner and all fragility descriptions are summarized in Table 4-2.

4.3.1.1 Reactor Pressure Vessel

The reactor pressure vessel is relatively insensitive to seismic loading since the governing design loads are normal operating pressure and blowdown type loading. The most critically stressed portions of the RPV, as reported in Reference 51, are the safe ends of the outlet nozzles. This area can be treated as piping just as well as RPV, since the most highly stressed area of the NSSS piping is also at the RPV outlet nozzle. A slightly different approach is taken for the RPV outlet nozzle safe end than for piping, however.

For the RPV, thermal expansion loading is considered in the normally applied loads but for piping, thermal expansion stress has not been considered as a contributor to failure loading. This approach for piping is consistent with the ASME code and is conservative for the RPV, since the ASME code does not consider thermal expansion loading as primary outside of the limits of reinforcement. The design margin is so large, however, that the conservatism would not appear to contribute significantly to calculated risk. Also, since the thermal expansion plus pressure stresses are less than yield, self-springing would not occur until a seismic event increased the stress beyond yield; thus, the thermal expansion load is present at the initiation of a seismic event.

The amount of elastic follow-up is, also, uncertain and it is considered prudent to include thermal expansion as a normal, sustained load for the RPV outlet nozzle.

In developing a range of strength for the RPV safe end, analytical limit type analysis procedures were utilized. First, the variability of material properties was considered, then the upper and lower bound limit moments were calculated based upon variability in limit moment shape factors for a given yield strength.

The yield strength for austenitic stainless steel, specified in the ASME Code, is, per Reference 48, about 1.65 standard deviations below the average value, corresponding to the 95% non-exceedance value, i.e., 95% of the data fall above the code specified value. Material strengths tend to be more lognormal than normal; thus, it was assumed that the coefficient of variation, from Reference 48, for yield strength is applicable to a lognormal distribution. Reference 48 indicates that the average yield strength of austenitic stainless steel is about 25% above the code specified value. Considering the average yield strength to be an approximate median value, the logarithmic standard deviation on material strength is computed, from Equation 2-9, to be 0.14. The random scatter of yield strength within any given heat is considered to have a logarithmic standard deviation of approximately 0.1 and the uncertainty of the median yield strength from heat to heat, expressed as a logarithmic standard deviation, is considered to be approximately 0.1.

In order to establish a range of strength for the safe end, an approach identical to that used for the reference piping fragility curve was used, i.e., and upper and lower bound on limit moment were established via the methodology of Reference 3, Q4-45-3 and Reference 49. The upper bound shape factor from Reference 3 is 2.67. The lower bound shape factor derived from Reference 49 is 1.71, assuming a through wall flaw of length equal to six times the pipe wall thickness. Since the probability of occurrence of the flaw is very small (assumed to be about

10^{-3}) the median shape factor was considered to be about three logarithmic standard deviation above the lower bound flawed condition and one logarithmic standard deviation below the derived upper bound. The median shape factor computed was 2.39 with a logarithmic standard deviation of 0.11. The resulting median limit moment capacity is 1.04×10^8 in-lbs.

As a check of the reasonableness of the derived limit moment capacity, the effective shape factors for several types of heavy wall pipe tests were averaged and the resulting mean shape factor was 2.35. This derivation included straight pipe collapse test data from References 33 and 34, piping system collapse test data from Reference 36 and piping fracture test data from Reference 30.

Having established a median moment capacity and its variability, the strength factor, F_S, is computed. Reference 3 provides RPV safe end stress intensities due to pressure, deadweight, thermal expansion and DBE. Converting these stress intensities into equivalent moments, the normal load P_N is computed to be 4.25×10^7 in-lbs and the DBE equivalent moment is 9.84×10^6 in lbs. Applying Equation 4-6, the strength factor, F_S, was computed to be 6.25. The logarithmic standard deviation is equal to the logarithmic standard deviation derived above for moment capacity.

Reference 14 recommends a ductility of 1.5 to 3.0 for design of critical piping. This is a design recommendation; thus, 3.0 is considered to be about a median value with 1.5 representing about a -2 logarithmic standard deviation value. Using these assumptions, and applying Equation 4-7, the median factor on ductility was computed to be:

$$F_\mu = 2.24$$

The logarithmic standard deviation, β_μ, was computed to be 0.30. The random portion of the ductility variability, β_R, is considered analogous to material strength variability and is considered to be about 0.15. The uncertainty portion, β_U, is then, 0.26.

Combining the strength and ductility factors results in a factor of safety on capacity of:

$$F_C = 14.0$$

The median capacity of the RPV safe end is then computed to be F_C times the equivalent DBE moment or, 1.38×10^8 in lbs.

Combining logarithmic standard deviations, the resulting variability on capacity can be expressed as:

$$\beta_C = 0.35$$

$$\beta_R = 0.20$$

$$\beta_U = 0.29$$

4.3.1.2 <u>Reactor Pressure Vessel Internals</u>

From Reference 3, the most critical area of the RPV internals is the guide tube to guide plate weld joint. For a Housner spectrum anchored to 0.25g for the OBE, the resulting seismic stresses are 51.2% of the code allowable of 1.5 Sm. Since gross guide tube deformation could hinder or stop control rod motion, the formation of a plastic hinge is considered a failure threshold. Since the failure mode is considered functional and not structural, no credit for ductility is taken.

The theoretical collapse moment for a thin tube without consideration of strain hardening, is $4/\pi$ times the moment to cause yielding on the outer fiber. This value is a lower bound and a more realistic shape factor must be considered for median centered results. Reference 52 compares experimental collapse moments to ASME code allowable stresses for Service Levels C and D for purposes of demonstrating functionability of pipe. For stainless steel pipe, the experimental data from References 33 and 34, normalized to code minimum specified yield, are compared to code allowables for both the room temperature and elevated temperature cases. At an elevated temperature of 550^{o}F, a specimen from Reference 52 with a D/t ratio of 15, and subjected to 2,000 psi internal pressure, is compared to the code Level C Service allowable of 1.8 Sm and a safety margin of 1.144 is quoted. This means that the static collapse moment is 1.144 times the Service Level C allowable at 550^{o}F considering internal pressure. The internal pressure tends to reduce collapse moment; thus, this comparison is on the conservative side.

From this information, a shape factor for collapse moment of 1.85 can be derived. This is considered to be an approximate median shape factor for pipes and tubes of approximately the same D/t ratio, operating at reactor coolant temperatures, with or without internal pressure. The theoretical lower bound shape factor of $4/\pi$ is considered to be about minus 2 logarithmic standard deviations below the median; thus, the logarithmic standard deviation on shape factor can be estimated, via Equation 2-9, to be 0.19. This is considered to be predominantly uncertainty such that for the plastic collapse shape factor:

$$\beta_R = 0.1$$

$$\beta_U = 0.16$$

Once the median shape factor of 1.86 is established for the guide tube geometry and operating temperature, the median factor of safety on collapse for the specified seismic loading can be computed. At the RPV internals operating temperature of approximately 600^{o}F, the computed OBE stress is 51.2% of the 1.5 S_m value or about 0.56 times the median yield strength. Therefore, the strength factor is the shape factor of 1.86 divided by the applied stress factor of 0.56 or, 3.32.

In addition to the variability on shape factor, the variability of material yield must be considered. The logarithmic standard deviation on yield strength of code materials is about 0.14, which is about half random and half uncertainty, or β_R = 0.1, β_U, = 0.1.

Combining the logarithmic standard deviations for shape factor and material yield, the variability is computed to be:

$$\beta_C = 0.24$$

$$\beta_R = 0.14$$

$$\beta_U = 0.19$$

Detailed information on the fundamental frequency of the guide tube assembly is now known; therefore, the frequency range was estimated to be between 5 and 15 Hz. Taking an average value of 10 Hz, the spectral acceleration for the 1/2% damping used for design is 0.83g. The median spectral acceleration capacity is then the strength factor times the design spectral acceleration or 2.75g S_a. The fragility parameter is then spectral acceleration at the reactor support pads at a frequency range between 5 and 15 Hz. The effect of uncertainty on the fundamental frequency is addressed in the response factors.

4.3.1.3 Steam Generator

Review of Reference 53 indicates that, for a conservative generic response spectrum, the seismic stresses are less than yield for all components of the steam generator. The steam generator tubes, per Reference 53, are the most critical item of the steam generator assembly. Based upon the design analysis, the tubes would not yield until the spectral acceleration at the system fundamental frequency was about 5 g's.

Q 4.17-1 from Reference 3 indicated that the NSSS component supports were limited to yield for normal plus DBE loads. Information from Westinghouse indicated that for Zion, the steam generator support columns are the most critically stressed item, with the normal and DBE loads consuming 32% and 38% of the faulted condition allowable respectively.

The construction material is ASTM A-588 with a 50 ksi minimum yield. Considering the median yield strength to be about 1.25 times the specified minimum, and applying Equation 4-6 with the above stated stress levels, the strength factor of safety is computed to be:

$$F_S = 2.45$$

The variability in this strength factor is due to variability in the yield strength, thus:

$$\beta_S = 0.14$$

$$\beta_R = 0.1$$

$$\beta_U = 0.1$$

Reference 54 recommends that for design of members loaded primarily in compression, the ductility should range from about 1.5 to 3.0. Since these are design values, 3.0 is considered to be about a median value and 1.5 to be approximately a minus 2 logarithmic standard deviation value.

Applying Equation 4-7, the median factor for ductility is:

$$F_\mu = 2.24$$

Considering the range of ductility from 1.5 to 3 as representing 2 logarithmic standard deviations and considering the uncertainty in the application of Equation 4-7, the variability can be defined as:

$$\beta_\mu = 0.31$$

$$\beta_R = 0.1$$

$$\beta_U = 0.29$$

Combining factors and logarithmic standard deviations, the overall capacity factor is:

$F_C = 5.5$

$\beta_C = 0.34$

$\beta_R = 0.14$

$\beta_U = 0.31$

Multiplying the computed factor times the original design spectral acceleration for the DBE results in a median capacity of 3.3g S_a at the 5 Hz fundamental NSSS system frequency. The resulting fragility parameter is spectral acceleration at 5 Hz at the steam generator support at elevation 590' of the reactor building.

4.3.1.4 Reactor Coolant Pump

For the reactor coolant pump, only pressure boundary and support failure are pertinent to the risk study; thus, function is not addressed.

The pump pressure boundary design is governed primarily by the high operating pressure and seismic loading is a less significant contributor. Information from the NSSS supplier indicates that the pump support stresses from seismic and normal loading are similar to the steam generator support stresses. The pump support fragility description is, therefore, identical to that of the steam generator. The median fragility level is 3.3g spectral acceleration at the 5 Hz NSSS system fundamental frequency. The applicable spectral acceleration is at the pump support/ reactor building interface at elevation 591'.

4.3.1.5 Pressurizer

The Zion pressurizer is an 1800 cubic foot cast head design. References 55 and 56 provide stress results for the pressurizer and its support skirt for a generic seismic analysis. Review of both reports indicates that the support skirt is the governing critical element for seismic loading. Reference 55 presents stress results from analysis of the 1,800 cu. ft. cast head pressurizer support skirt for an equivalent static load of 0.96g horizontal and 0.64g vertical. Using stress results from Reference 55 and average properties of the SA 516 Gr-70 flange, the strength factor is computed to be 1.70. Bolting was examined and a corresponding strength factor was computed to be 1.49 which is slightly less. Bolting material is AISI 4140, but the level of heat treat is not known. Reference 55 stated that the minimum S_m for bolting had to be greater than 13 ksi which would allow the use of relatively low strength bolts. It was therefore assumed that the bolting material was in the normalized condition with a minimum yield strength of 75 ksi.

The strength factor for bolting is slightly less than that computed for the skirt. Bolting is also considered to have a much lower ductility. The pressurizer fragility description was, consequently, based on bolting strength and ductility.

The strength factor for the pressurizer fragility description, based upon bolting is:

$$F_S = 1.49$$

The variability on this strength factor consists of material property variability taken as $\beta = 0.14$ plus an additional variability due to assumptions made. This is considered to be an additional β of 0.1, resulting in a total logarithmic standard deviation on strength of 0.17. The random portion is due to random material property variation and is estimated to be about 0.1. The portion attributed to uncertainty is then, 0.14.

Median ductility for bolting is considered to be about 1.5 with a minimum value of 1.0 to represent pullout of anchorage. The median factor of safety for ductility from Equation 4-7 is then:

$$F_{\mu} = 1.41$$

The logarithmic standard deviation on this factor, considering both variability in ductility and uncertainty in use of Equation 4-6 is:

$$\beta_{\mu} = 0.26$$

$$\beta_R = 0.1$$

$$\beta_U = 0.24$$

Combining factors and variabilities, the capacity factor and its dispersion can be represented as:

$$F_C = 2.10$$

$$\beta_C = 0.31$$

$$\beta_R = 0.14$$

$$\beta_U = 0.28$$

Multiplying the capacity factor times the equivalent static load used in the generic design results in a median capacity of 2.0g. The pressurizer fundamental frequency is in the 18-22 Hz range; thus, the fragility parameter for the pressurizer is spectra acceleration for the frequency range of 18-22 Hz.

4.3.1.6 Control Rod Drives

The Zion nuclear power plant uses Model 106A control rod drive assemblies. Detailed information on the control rod drive mechanisms, other than a generic functional description from Reference 57, was not available. The control rods are designed to drop by gravity if a scram is initiated and are supported laterally by the guide tubes; thus, it is assumed that as long as the guide tubes do not deform significantly that the rods can drop and perform their intended function.

In Section 4.3.1.2, a median capacity and variability for the guide tubes was developed and this is considered to be applicable to the control rod drive mechanism.

4.3.1.7 Other Safety-Related Equipment Whose Seismic Failure Modes Are Controlled by Structural Failure

Numerous other safety-related pumps, valves, heat exchangers and pressure vessel reports were reviewed and for those components, whose seismic failure modes were governed by structural failure, fragility descriptions were developed in the same manner as described in Sections 4.3.1.1 through 4.3.1.6 for NSSS components. Fragility descriptions for all plant specific and generic components are summarized in Table 4-2. The safety-related plant specific components included in the plant specific structural failure mode category are:

Safety Injection Pump
Residual Heat Exchanger
Component Cooling Water Heat Exchanger
Accumulator Tank
Boron Injection Tank
Main Steam Isolation Valve
Condensate Storage Tank
Diesel Oil Storage Tank
Buried Service Water Pipe from Crib House
Buried Auxiliary Feedwater Pipe from Condensate Storage Tank

Service Water Pumps
Battery Racks
Safety Injection Pump

In the cases of the Condensate Storage Tank, Diesel Oil Storage Tank and Buried Pipe, new analyses were conducted to determine capacities.

4.3.2 Plant Specific Functional Capacities Derived from Design Reports

Major equipment items, whose failure modes have been determined by design analysis to be functional rather than structural, are addressed in this section. In addressing functional failure modes, ductility, i.e., inelastic energy absorption, is not a consideration since the functional limits may be within the realm of subsystem elastic response.

4.3.2.1 Containment Fan Coolers

For the Zion containment fan coolers, there are two functional failure modes.

1. Rubbing of the fan blades on the fan housing.
2. Rubbing of the motor rotor on the motor housing.

Calculated deflections under seismic loading and allowable deflections are given in the design report. The safety factor between the allowable vs calculated deflection is slightly greater for the motor rotor and housing than for the fan and its housing; therefore, the fan deflection is considered the most likely failure but the rotor deflection margin is close. Tolerances were not available; therefore, it was assumed that the allowable deflection was a worst case manufacturing tolerance stack up equivalent to a -3β value on clearance. Considering the size of the fan cooler and normal fabrication tolerances of equipment of this type, the median clearances were estimated. Using estimates of median clearance and the calculated deflections, the median factors of safety on rubbing were computed to be 2.66 for the fan blade rubbing and 2.85 for the motor rotor rubbing. The logarithmic standard deviations on these factors can be derived from assumptions on the tolerances and are computed to be 0.23 for the fan and 0.24 for the motor rotor. The variabilities are made up of both randomness in distortion that may take place during operation and uncertainty in the actual finished dimensions. The distribution of variability due to randomness and uncertainty is estimated to be:

Fan Rubbing	Motor Rotor Rubbing
$\beta_R = 0.15$	$\beta_R = 0.15$
$\beta_U = 0.17$	$\beta_U = 0.19$

4.3.2.2 Residual Heat Removal Pumps (RHR)

The RHR pumps in Zion were analyzed for seismic loading as part of a system dynamic model which included attached piping. A generic response spectrum was used. The two most critical areas were identified as the pump holddown bolts and the impeller deflection. The minimum factor of safety was associated with impeller deflection.

Calculated deflection was 0.0099 in. and the stated allowable was 0.0105 in. Tolerances are not known; thus, it was assumed that the worst case tolerance stack up, equivalent to a -3β value, resulted in the minimum allowable deflection of 0.0105 in. Considering the size of the impeller, the method of fabrication of the impeller and pump housing and normal machine shop tolerances, the median clearance is estimated to be 0.0145 in. The resulting median factor on capacity is 1.46 with a logarithmic standard deviation, β_C, approximately equal to 0.11. The resulting variability is mostly uncertainty in the actual clearance in each unit with a small amount of randomness inherent in the clearance under operating conditions. The estimated variabilities due to randomness and uncertainty are:

$\beta_R = 0.05$, $\beta_U = 0.10$

Multiplying the safety factor times the design spectral acceleration, at the equipment fundamental frequency of 7 Hz, results in a median spectral acceleration capacity of 3.2g.

The mounting bolt capacity is much greater and the median capacity is 11.7g spectral acceleration at 7 Hz.

4.3.2.3 Centrifugal Charging Pump

The Zion centrifugal charging pump was analyzed using the static coefficient method for a 2.0g acceleration applied simultaneously in the horizontal and vertical directions. Sine sweep testing of the pump revealed that the lowest natural frequency of the pump motor assembly was 31.8 Hz in the pump gear; thus, the rigid body static coefficient method was validated.

A calculated thrust bearing pad load of 321 psi was close to the allowable load of 343 psi. The allowable load is a vendor catalogue load for continuous service. Bearings can frequently withstand at least twice the rated load for short durations; thus, it was assumed that the median short term load capacity was twice the rated continuous service load, or 686 psi. Using these numbers, the median factor of safety on bearing capacity is 2.13.

Assuming the allowable continuous duty load to be at least a -3β capacity for short term loading, the logarithmic standard deviation is calculated to be

$$\beta_C = 0.23$$

The estimated random and uncertainty variabilities associated with bearing load capacity are:

$$\beta_R = 0.15 \qquad \beta_U = 0.17$$

4.3.3 Generic Structural Capacities Derived from Design Criteria

In the majority of cases in risk studies, all detailed information regarding resulting stresses, deflections, bearing loads, etc., for safety-related equipment is not readily available to the risk analyst. Classes of equipment must then be treated generically and the fragility descriptions must be derived from knowledge of design criteria and methods, service experience, etc. In this section, fragility descriptions are developed for those items of equipment whose failure modes are structural and for which design reports were not readily available.

Typically, for passive mechanical equipment designed in the Zion era, the seismic design was based upon the support capacity. This is the most logical location for a seismic failure to occur and, as such, the remainder of passive equipment, for which design reports were not readily available, are treated generically by defining a generic support fragility.

Supports were typically designed to a working stress level for OBE. The ASME code working stress level for carbon steel is the lesser of 5/8 of the yield strength or 1/4 of the ultimate strength. Assuming a common carbon steel material such as SA 516-Gr 60 or equivalent, the allowable stress would be based upon 1/4 the ultimate strength.

For loading on the supports, the normal load was assumed to range from 0.0 to 0.5 times the allowable design load, the OBE load was assumed to vary from 0.2 to 0.8 times the allowable design load and the combined normal plus OBE load was assumed to range from 0.2 to 1.1 times the allowable design load.

Considering these load ranges and the range of material properties, the median strength factor is calculated to be

$$F_S = 6.33$$

The variability on this factor was derived to be

$$\beta_S = 0.40$$

$$\beta_R = 0.18$$

$$\beta_U = 0.36$$

Reference 54 recommends lower ductility factors for light equipment than for heavy equipment. Using the guidance of Reference 54, the estimated median ductilities are 1.5 for light equipment and 2.0 for heavy equipment. The associated ductility factors and their variabilities are:

Light	Heavy
F_μ = 1.41	F_μ = 1.73
β_μ = 0.26	β_μ = 0.28
β_R = 0.10	β_R = 0.10
β_U = 0.24	β_U = 0.26

The resulting capacity factors for the OBE and their variabilities are:

Light	Heavy
F_C = 9.0	F_C = 11.0
β_C = 0.48	β_C = 0.49
β_R = 0.21	β_R = 0.21
β_U = 0.43	β_U = 0.44

The capacity factor times the design acceleration level specified for the equipment results in the acceleration capacity. Since the specified design acceleration varied from building to building and floor to floor, the generic acceleration capacities would likewise vary. Since the fundamental frequency is not known for generic equipment, capacities can be referenced to the zero period acceleration of the applicable floor spectra. Most of the equipment is sufficiently rigid that the fundamental frequency would not coincide with high amplification regions of the response spectra and using the zero period acceleration as the fragility parameter is justified. Table 4-3 lists the zero period acceleration capacities and variabilities of generic equipment that fail in a structural mode.

Fragility descriptions for ducting were derived in a similar manner and are described in Table 4-4.

4.3.4 Pipe Supports

Individual pipe support fragility descriptions would be impractical to develop; consequently, a generic treatment is applied for pipe supports. Lawrence Livermore Laboratory (LLL) has compiled a list of pipe support design loads as a function of pipe diameter. The best fit of the design load vs pipe diameter and the variability about the best fit can be quantified from that study. A generic fragility description can then be based upon the factor of safety in the original design load.

Two types of seismic supports are considered; rigid rod type supports that carry dead weight of the piping plus vertical seismic response and lateral supports, either rigid or snubbers, which carry seismic load only.

Design criteria for piping supports were not delineated in the piping design specification. Most piping was designed to the requirements of the ANSI B31.1 Code for power piping, which contains design criteria for piping supports. The basic allowable stress for supports is either the allowable value, S, taken from the allowable pipe stress tables or, if S values are not given for the particular support material, the basic allowable is 1/4 of the ultimate strength. In addition, there is a derating factor of 0.75 for threaded and welded connections and an occasional load factor of 1.2.

Generally, when non-nuclear codes are applied to nuclear power plants, working stress allowables are considered to be applicable to normal plus OBE loading. For normal plus SSE (DBE in the case of Zion), or other faulted condition loading, the allowable stresses are usually increased. Review of the FSAR and of several design reports indicated that the minimum specified yield strength was generally used as a faulted condition loading stress acceptance criterion. It was, therefore, assumed that dual criteria existed for Zion pipe supports and that the criteria were:

1. Dead load plus thermal plus OBE ≤ (1.2) (1/4) S_u
2. Dead load plus thermal plus SSE ≤ S_y

Considering the code materials properties spread between yield and ultimate and assuming that the SSE load is approximately double the OBE load, Criterion 1 would always govern. Criterion 2 could govern for other dynamic loading events such as water hammer and blowdown but could never govern seismic design. Fragility relationships were, therefore, developed based on Criterion 1 governing the seismic design.

Subsequent to those assumptions, LLL confirmed with Sargent and Lundy that Criterion 1 was the governing criterion for seismic design of supports.

4.3.4.1 Vertical Rod Hangers

Vertical rod hangers can carry very little compression loading; therefore, a check was first made to determine if the vertical seismic load can exceed 1g. Vertical spectra were not provided for design of Zion equipment. Instead, an equivalent static force of 0.06g was specified for OBE. This was unrealistically low for piping which can respond significantly to vertical excitation. The A/E, therefore, elected to apply 2/3 of the horizontal spectra in the vertical direction. Examination of the Zion design response spectra for the auxiliary and containment buildings revealed that the DBE spectral acceleration for the vertical direction could vary from 0.13 to 1.0g depending upon the elevation and frequency of the piping. These values are very conservative since design spectra were based on very conservative damping values. Also, the Zion floor spectra were generated using an earthquake time history that resulted in a spectrum that significantly exceeded the site design basis spectrum. This indicates that the peak spectral acceleration would not exceed the dead weight gravity loading for seismic levels considerably in excess of the DBE. Further examination of the floor spectra reveals that, at any elevation in either building, the spectral acceleration within the predominant frequency range of piping systems can vary by about a factor of two or slightly greater. It was, therefore, assumed that, within a piping system, vertical support designs were based on a maximum OBE load equal to the dead weight load. It is further assumed that the minimum OBE load was about one-half the dead weight load. These assumptions provide a range of seismic to dead weight loading to be represented in probabilistic terms.

Further assumptions made regarding pipe support design were:

1. Supports were constructed of carbon steel with a minimum yield strength at ambient temperature of 25 ksi and a minimum ultimate strength of 50 ksi. These values correspond to the weaker grades of low carbon steel which are typically used for pipe supports.

2. Most supports operate at ambient temperature; thus, no temperature derating was considered.

3. Median strength values are 1.25 times minimum values for code materials. The minimum values are set at about the 95% probability of exceedance value, which corresponds to 1.65 logarithmic standard deviation from the median.

4. Rod hanger designs are similar for a given system and pipe size such that the rods are sized for the maximum load, P_D, at any point in the system and most are stressed to values less than this.

5. Rod hangers are either threaded or welded; therefore, the 25% reduction in allowable stress is applied.

The strength factor, F_S can be computed from:

$$F_S = \frac{\dfrac{\sigma_y}{\sigma_d} - \dfrac{\sigma_n}{\sigma_d}}{\dfrac{\sigma_t}{\sigma_d} - \dfrac{\sigma_n}{\sigma_d}} \qquad (4\text{-}8)$$

The normal load, σ_n, to design load σ_d ratio is assumed to vary from 0.2 to 0.8. The total load, σ_t, to design load σ_d, ratio is assumed to vary from 0.3 to 1.1. The yield strength to design load ratio also varies due to the variability in yield strength. Assuming that the median yield strength is 1.25 times the specified minimum value and that this factor represents a 1.65 logarithmic standard deviation spread, the logarithmic standard deviation on yield strength is 0.14.

Working first with median yield strength and applying Equation 4-8 to extremes of load ratios, and remembering that the OBE load will vary from one-half to one times the dead weight load, the strength factor, F_s, was computed to vary from 5.2 to 25.8. Considering these values to be approximately the $\pm$ 2β limits for loading variation, the median strength factor and logarithmic standard deviation can be determined from Equation 2-8 to be 11.6 and 0.4, respectively.

Accounting for the additional variability due to material yield strength, the logarithmic standard deviation on strength is $\beta_S = 0.42$.

The additional capacity of pipe supports due to energy absorption capability must be considered. Reference 54 recommends, for steel elements in tension or bending, that the allowable ductility for design should range from 2.5 to 10. These values are conservative design values but will be used as representative of simple structural elements. Since support designs are considered to be of welded or threaded construction, the recommended element ductility was reduced by a factor of 2, resulting in a range of 1.25 to 5. The factor of safety due to energy absorption was estimated from Equation 4-7 to be 1.93 with a β of 0.30.

The total capacity factor for vertical rod hanger pipe supports is then the product of the strength factor and the energy absorption factor and was computed to be 22.4. The logarithmic standard deviation on the capacity factor was computed from the SRSS of the capacity and ductility logarithmic standard deviations.

$$\beta_C = \sqrt{\beta_S^2 + \beta_\mu^2} = 0.52$$

In the strength factor, the material variability is considered to be about half random and half uncertainty, with the loading considered to be almost all uncertainty. The random variability for strength, β_{R_S}, is estimated to be about 0.20 and β_{U_S} is estimated to be about 0.37. The dispersion on the energy absorption is considered to be predominantly uncertainty. β_R is assumed to be 0.1 and β_U to be 0.28. The combined random and uncertainty logarithmic standard deviations are:

$$\beta_R = 0.22$$

$$\beta_U = 0.47$$

The following table summarizes the factors and dispersions for vertical rod hangers.

Factor	F	β_R	β_U	β_C
Strength	11.6	0.20	0.37	0.40
Ductility	1.93	0.10	0.28	0.30
Capacity	22.4	0.22	0.47	0.52

The associated fragility parameter is calculated load, P, divided by supported load, P_D with P/P_D equal to 22.4 with the logarithmic standard deviation equal to 0.52.

4.3.4.2 Horizontal Snubbers and Rigid Rods

Horizontal pipe supports do not carry dead weight load and only rigid supports can carry thermal load induced by restraint of piping thermal expansion. For purposes of capacity estimates, it is assumed that lateral supports carry only seismic loads and that the load will range from 0.2 to 1.10 times the design load, P_D. Using the ranges of yield strength and other assumptions as used for vertical supports, and applying Equation 4-8, the median strength factor is computed to be 6.2 with a β_S of 0.45.

The random portion is due primarily to random variability in yield strength and random variability in the failure mode and is estimated to be 0.20. The uncertainty is primarily due to the assumed loading range and is computed to be 0.40.

Since connections on horizontal pipe supports will be similar to vertical supports, the energy absorption capacity factor and its dispersion will be the same as for vertical hangers. The factors for horizontal snubbers and their dispersions are tabulated below.

Factor	F	β_R	β_U	β_C
Strength	6.2	0.20	0.40	0.45
Ductility	1.93	0.10	0.28	0.30
Capacity	12.0	0.22	0.49	0.54

The associated fragility parameter is calculated load, P, divided by support design load, P_D, with P/P_D equal to 12.0 with logarithmic standard deviation, β, of 0.54.

4.3.5 Capacities Derived from Tests for Higher Seismic Zones

Reactor protection system electrical and electronic equipment, plus the static inverters, have been qualified by Westinghouse for high seismic zone environments significantly greater than the Zion seismic environment specified for the auxiliary building at elevation 642'. References 11 and 12 document the high seismic zone tests.

Testing was conducted using the sine beat method to excite a single axis at a time. The input level varied with frequency, but in the predominant frequency range of the electrical equipment cabinets (5-10 Hz), the input acceleration was 1.5g. Ten sine waves per beat were typically used in the sine beat testing, wherein the sine waves would increase in amplitude for five cycles then decrease for the remaining five cycles. Median damping, as suggested by Reference 58, is about 5%. This is further verified by examining response to similar equipment tested in the SAFEGUARD program, Reference 13. At 5% damping, the ten cycle input has an amplification factor of about 7.6, resulting in approximately an 11.4g response, i.e., the response spectrum from 5-10 Hz has a spectral acceleration of 11.4g.

No failures were observed at this test level. In the case of the static inverter, when the input acceleration was increased by a factor of $\sqrt{2}$ a minor malfunction was observed. Other equipment was not tested at higher levels so that a fragility level was not experimentally determined.

A single qualification test does not provide much insight into fragility levels; however, when a number of different items of the same generic type survive a qualification level, then there is reason to believe that the qualification level is in the lower tail of the fragility curve, but the exact fragility level is still indeterminate. Engineering judgments as to the median fragility and its variability must, therefore, be made.

Since a $\sqrt{2}$ increase in one test article caused minor malfunctions, where several test articles functioned without incident at the specified test level, it was assumed that the specified spectral acceleration of 11.4g was about minus one logarithmic standard deviation below the median and that the median is approximately $\sqrt{2}$ above the specified test level of 11.4g spectral acceleration. The fragility level was then established at 16.1g spectral acceleration with a logarithmic standard deviation of 0.35. The contribution to the variability due to randomness, β_R, is estimated to be about 0.2 with the uncertainty, β_U, equal to about 0.29.

In this case, a factor of safety need not be derived since the fragility description was derived directly. The fragility parameter is spectral acceleration for a frequency range of 5-10 Hz and at a median damping value of 5%.

4.3.6 Cable Trays

Reference 59 portrays the criterion used for design of Zion cable trays. For flexible cable tray supports, a static coefficient method was used, referenced to the peak spectral acceleration of the applicable floor spectra at 5% damping. For rigid cross-braced cable trays, the ZPA was used for seismic design.

Reference 60 reports results of some 2,000 dynamic tests conducted on cable tray systems. Some general conclusions regarding cable tray capacities are reached in the paper that indicate large seismic capacities. The large capacities result, in a significant part, to the large amount of damping measured in cable tray systems.

In order to select a fragility description for use in the Zion study, both the original design criteria and the test summary were used to estimate median fragility levels. A generic structural capacity factor was developed using the methodology of Section 4.3.3. When response factors, that accounted for conservatism in the Zion floor spectra and the high level of damping reported in Reference 60, were included in the fragility description, the resulting capacity was slightly larger than estimated from the test data summary. Reference 60 was, therefore, used as a basis for the fragility description.

Reference 60 is only a brief summary of a very extensive test report which was not available for our use. Consequently, the fragility description is very approximate. Personal communication with the author of Reference 60 helped to clarify some of the results reported in the Reference.

Cable tray tests described in Reference 60 were conducted on a biaxial shake table. Regulatory Guide 1.60 spectral shapes were used in synthesizing the time history inputs. In some 2,000 tests at ZPA input levels of 1 to 3g's, no functional failures or complete structural failures occurred in strut supported cable tray systems. Rod supported systems had significantly lower capacity; however, in accordance with Zion specifications for cable tray systems, all safety-related systems were designed with bracing to resist seismic loading, such that the rod supported cable tray system tests are not considered applicable to Zion safety-related systems. Rod supported trays do exist in the plant but, as previously stated, they are not safety related.

Assuming 3g's ZPA to be an approximate median capacity and the 1g lower test level to be about a -2β value, the computed logarithmic standard deviation on capacity is about 0.55 which is about what would be expected for such a generic treatment of capacity. Most of the critical cable systems are in the cable spreading room which is located fairly high in the auxiliary building at elevation 630'. The ZPA for the DBE at elevation 630' is about 0.36g, resulting in a capacity factor of about 8.33. The logarithmic standard deviation on that factor is about 0.55, of which β_R is estimated to be about 0.3 with β_U about 0.46. The fragility parameter specified for cable trays will be the zero period acceleration at the floor level under consideration.

4.3.7 Offsite Power

Failure of offsite power is governed primarily by failure of ceramic insulators. A review of insulator failure in six major earthquakes, ranging from 0.11g to 0.4g peak ground acceleration, resulted in a median capacity for ceramic insulators of:

$$\check{A} = 0.20g$$

where $\check{A}$ is the median peak ground acceleration capacity. The logarithmic standard deviation on this value is about 0.4, of which the estimated randomness, β_R, is about 0.15 and β_U is about 0.37.

4.3.8 Generic Capacities Derived from Military Shock Test Data

Typically, when nuclear plant equipment is qualified for a seismic environment by test, the Test Response Spectrum (TRS) envelops the Required Response Spectrum (RRS), sometimes by a significant amount and sometimes by only a small amount. In risk studies, a mean or median fragility level of equipment, and the variability about this value, must be established. Since fragility testing is rarely conducted for nuclear power plant equipment, it is difficult to establish fragility levels above the qualification level.

The few test reports examined for Zion specific equipment indicated that large margins were not inherent in the qualification testing levels; thus, a conservative approach to estimating fragility levels could not be taken as was done for the reactor protection system. Instead, a data base of military shock tests of similar, off-the-shelf equipment, was utilized to develop fragility descriptions for several generic categories of equipment.

In the SAFEGUARD program, a comprehensive testing program was undertaken to demonstrate acceptable reliability of power and process equipment installed in a hardened radar installation. Reference 13 summarizes the results of that program. References 61 and 63 portray the methodology utilized to assure a high reliability of the equipment when subjected to severe nuclear weapons effects ground shocks.

In the SAFEGUARD program, off-the-shelf equipment was procured rather than procuring specially engineered equipment qualified for shock and vibration environments. The equipment was very similar to equipment installed in nuclear power plants and was procured in the same time frame as procurement of Zion equipment. Consequently, the test performance of SAFEGUARD equipment should be indicative of balance of plant nuclear power plant equipment purchased approximately ten years ago. At that time, most manufacturers of commercial equipment were unsure of ultimate shock and vibration capacity of their products and did not have experience in qualification for shock and earthquake environments. Procurement specifications that contained severe shock environments would have resulted in prohibitive cost and delay in the SAFEGUARD program. It was, therefore, decided to conduct selected fragility and shock environment qualification tests on generic equipment and develop the reliability of untested equipment by a pseudo-probabilistic methodology. Some 400 component and system tests were conducted in support of the qualification of some 30,000 critical items in the SAFEGUARD installation. The program plan and methodology for assuring reliability of untested equipment are contained in Reference 62.

Initially, in the SAFEGUARD program, fragility testing was conducted for selected equipment items. This proved to be very costly and further testing was restricted to go, no-go qualification testing. The resulting data base is predominantly shock test results of equipment for which no permanent functional failure occurred. In many of the tests, however, some structural damage was observed and in many of the electrical and control equipment tests, electrical malfunctions occurred that were only temporary or intermittent. In many cases, at the shock test levels applied, structural damage or functional anomolies noted would appear to be near the fragility level. In other cases, however, no evidence of damage or functional anomolies was present.

After examination of the data base, it was concluded that two separate methodologies should be applied to develop fragility relationships for generic classes of equipment. For equipment that is not complex, and for which the generic test data generally indicated no functional anomolies, the pseudo-probabilistic methodology, developed by the U.S. Corps of Engineers for subsystem hardness assurance of SAFEGUARD equipment, was applied. For complex electrical and control equipment, detailed comparisons of Zion equipment construction features to the tested equipment was not feasible within the resources of the SSMRP. The application of the Corps of Engineers pseudo-probabilistic methodology requires such comparisons; thus, a different methodology was devised to utilize the test data to develop fragility descriptions. The tests of electrical instrumentation and control equipment often resulted in functional anomolies, such as relay chatter and breaker trip, which were common to many generic classes of equipment. The data were, consequently, used to develop fragility descriptions by failure mode, which can be combined for several generic classes of equipment. For purposes of abbreviated reference to the applicable methodology, the application of the Corps of Engineers methodology is referred to as Method A and the development of fragility descriptions by failure mode is referred to as Method B.

Fragility descriptions for the following generic categories of equipment were developed by the methods indicated.

Method A	Method B
Large Hydraulic and Air Operated Valves	Swtich Gear
Large Check and Spring Relief Valves	Instrument Panels & Racks
Small Miscellaneous Valves	Control Panel & Racks
Batteries	Relay Cabinets
Transformers	Motor Control Centers
Local Instruments	Breaker Panels
Air Conditioning and Air Handling Units	
Pumps and Compressors	

4.3.8.1 Description and Applicability of Shock Tests

The SAFEGUARD program shock test environments were defined as in-structure response spectra for various equipment locations. The spectra were not typical of earthquake spectra in that the shock spectra emphasized the high frequency, high spectral acceleration regions typical of blast loading and contained very little response to frequencies below about 5 Hz. Figure 4-3 is a typical shock test spectra for hard mounted equipment. Earthquake in-structure response spectra typically peak in the 2-10 Hz range with essentially zero amplified response beyond 20-25 Hz. The shock test data are felt, however, to have applicability to nuclear power plant equipment, especially that equipment that fails in a functional mode. It was generally observed during the shock test program that the lower frequency content of the shock spectra was the most significant contributor to malfunctions and certainly to structural failures. There is no positive way to separate out frequency effects from the test data since almost all tests were conducted with broadband shock spectra typical of Figure 4-3. A few tests were, however, conducted at lower frequency input that demonstrated that electrical malfunction problems with large switchgear were due primarily to lower frequency input. The shock test data are not particularly applicable to equipment whose fundamental frequency is below 5 Hz. Fortunately, most equipment items of concern have fundamental frequencies considerably above 5 Hz and the shock test data are felt to be a good indicator of seismic resistance.

The terminology "shock tests" was used in the SAFEGUARD program to describe a complex time history input of 2-5 seconds duration. The tests were not, as might be reasoned from the title, single shock pulse inputs. They were, instead, complex waveform tests which typically consisted of several superimposed sine beat inputs that would result in the required response spectrum. Test response spectra were specified as undamped spectra. For the SSMRP Fragility Project, fragility descriptions in terms of damped spectral accelerations are desired. Consequently, the SAFEGUARD program undamped test spectra were compared to damped spectra in order to derive a scale factor, and uncertainty in the scale factor, for converting undamped spectral accelerations to damped spectral accelerations. Reference 63 provides a typical multiple sine beat input to generate a shock spectra similar to that shown in Figure 4-4. The multiple sine beat input was run through a response spectrum generation program and a comparison was made of damped and undamped spectra. The five percent damped spectral accelerations were typically about 2/3 of the undamped spectral accelerations. The variability on this scale factor, expressed as a logarithmic standard deviation, was about 0.13.

Five percent damping appears to be a reasonable median estimate for equipment and electrical instrumentation and control cabinets. Damping values could not be derived from the SAFEGUARD test data without extensive engineering analysis of the equipment and correlation to measured responses. The five percent median estimate was derived from limited observations of response of essentially single-degree-of-freedom equipment to steady-state harmonic inputs. Reference 58 also suggests five percent as a median value for equipment responding at the DBE or greater level. Most fragility descriptions, referenced to spectral acceleration, are keyed to five percent damping and the above scale factor was used in developing fragility descriptions.

4.3.8.2 Application of U.S. Corps of Engineers Pseudo-Probabilistic Methodology, Method A

The U.S. Corps of Engineers methodology utilized to assure high shock environment reliability of untested equipment is described in Reference 62. Chapter 5 of Reference 62 is included as Appendix A to describe the procedure and assumptions. The pseudo-probabilistic procedure is based upon comparing an achieved test level, modified for differences between the test article and the article to be qualified, to an upper bound environment. If the ratio was equal to 1.0 or greater the equipment was considered to have demonstrated a reliability in excess of 97.7%. Expressed mathematically:

$$Hv = \frac{\bar{T} - 3\sigma_T}{\bar{E} + 3\sigma_E} \qquad (4\text{-}9)$$

where Hv is the hardness index, $T-3\sigma_T$ is the lower bound (-3 standard deviation) hardness or fragility level and $E + 3\sigma_E$ is the upper bound (+3 standard deviation) environment. The environment for SAFEGUARD is of no interest to the SSMRP but the mean and standard deviation of the fragility level are of paramount interest. The mean fragility level and its standard deviation are defined by the product of four factors, f_1 through f_4. These four factors account for:

f_1 - Highest achieved test level of similar equipment

f_2 - Similarity of component to be qualified to tested component.

f_3 - Similarity of test conditions to actual expected conditions of component to be qualified.

f_4 - Performance of tested component.

Detailed procedures are provided in Appendix A for quantifying the upper and lower values of each factor. The basis for the quantification of each factor is not documented in any of the U.S. Corps of Engineers reference documents that were reviewed. Personal communication with one of the equipment qualification project engineers, Reference 64, indicated that the quantification of the f factor ranges was the result of iteration among several engineers from the various organizations involved in SAFEGUARD. This was essentially a Delphi procedure wherein several experts converged upon a range of values for the four factors and a procedure to quantify the values.

Reference 62 states that the product of the upper and lower values of the four f factors represent the plus and minus three standard deviation values of a normal distribution (within engineering accuracy). The basis for this is stated to be unpublished trial data. In applying the methodology to Zion equipment, the above assumptions were utilized and fragility descriptions are derived based upon properties of the normal distribution. Since none of the fragility descriptions can be exactly defined, the exact distribution of capacity is not readily determinable and, within one standard deviation, most assumptions made on the distribution will be within the engineering accuracy obtainable from the limited data. In Phase I of the SSMRP, fragility and response descriptions are limited to normal and lognormal distributions and may be approximately converted from one distribution to the other by a least squares curve fit between defined bounds. Since all other fragility descriptions in this report are derived on the basis of a lognormal distribution of capacity, the fragility description derived, using the

Corps of Engineers methodology, are converted to lognormal distributions by a least squares curve fit process. Both the normal and lognormal fragility description are contained in Table 4-5.

In applying the Corps of Engineers methodology to generic categories of equipment for SSMRP, some modifications to the methodology were necessary. In the SAFEGUARD program, each individual equipment item was evaluated by the methodology in Appendix A. In evaluating an individual item of equipment, a comparison was first made of the item to be qualified to items that were tested. The highest test spectrum, for the tested item that most closely resembled the item to be qualified, was used to determine the f_1 factor. In determining the f_2 and f_3 factors, detailed drawings of the tested article and the article to be qualified were reviewed and detailed comparisons were made. The resources of the SSMRP project do not provide for application of the Corps of Engineers methodology in such great detail. Instead, equipment was examined by generic categories and all test levels of equipment in those generic categories were considered. The net result is a greater variance on fragility than would be derived if equipment were tested individually. In determining f_1 factors, the range of test levels for the range of equipment fundamental frequencies is used to define upper and lower bounds of f_1. The f_1 factor, as defined by the Corps of Engineers methodology, is a dimensionless number. The achieved test level is divided by a reference mean environment to derive the factor. Likewise, the plus three sigma environment that appears in the denominator of the Equation 4-9 for hardness index, Hv, is divided by the same mean environment. By comparing the test level spectrum to an environmental spectrum, and having knowledge of the equipment fundamental frequency, the range of f_1 could be established quite accurately. Since the Zion seismic environment varies for each equipment location, a generic treatment of fragility requires some modification in defining f_1. It is not necessary to non-dimensionalize f_1, since the end item of interest is a fragility level. Most of the SAFEGUARD shock test spectra were relatively flat in the equipment frequency range of interest (> 5 Hz). It is, therefore, adequate to define f_1 as a spectral acceleration range within the expected frequency range of the equipment contained within a generic category. The product of f_1 through f_4 will then have units of g's. The fragility description will identify the fragility parameter as spectral acceleration with an associated frequency range and damping value. See Section 2.1 for a more detailed description of interfaces between the response and fragility descriptions.

In determining f_2 and f_3, exact comparisons of equipment in Zion to equipment tested are not feasibile; thus, the maximum ranges of individual variables, that combine to provide f_2 and f_3 upper and lower bounds, are often applied. A great deal of engineering judgment was made for each case. When a large amount of uncertainty was present, the maximum ranges of variables were selected to quantify that uncertainty. In cases where there was less uncertainty about parameters of the test article vs a Zion generic category, the variable ranges were selected to reflect this knowledge.

For the most part, equipment fragilities developed using the Corps of Engineers methodology were based on successful tests, i.e., no permanent functional failures were observed during the tests. The f_4 factor provides for degrading the test results based upon performance. In most cases f_4 was equal to 1.0, reflecting successful testing. In cases where significant structural damage was noted or where functional anomolies occurred, a factor less than 1.0 was selected to reflect a marginal situation at the achieved test level.

Table 4-6 summarizes the derivation of f factors and the resulting upper and lower bound on the product of the factors. Table 4-5 defines the fragility descriptions in terms of both normal and lognormal distributions.

4.3.8.3 Derivation of Fragility by Failure Mode for Electrical and Control Equipment, Method B

Application of the Corps of Engineers Psuedo-Probabilistic Methodology to complex electrical and control equipment was attempted on a generic basis but difficulty was experienced in the generic treatment. The major problem was, unlike most mechanical equipment tested, that malfunctions often occurred at the lowest test levels achieved. Because of the frequent malfunctions observed, quantification of the f_4 factor, which evaluates functional anomolies, became too subjective. In cases where functional anomolies occurred at the lowest test level, there was little basis to estimate a level at which no functional anomolies would occur.

The predominant failure modes observed in all electrical and control equipment were relay chatter and breaker trip. Neither of these failure modes results, in all cases, in failure of the equipment to perform its intended function. They are, however, functional failures which must be addressed by the systems analyst. Relay chatter is a functional failure mode that is self-correcting after the vibratory earthquake motion ceases. In this case, the function of the system is interrupted for a period of seconds. Relay or breaker trip is a functional failure mode that requires some form of manual or remote electrical reset and can potentially interrupt function for minutes to hours.

The general trend of the shock test results on electrical and control equipment was to experience relay chatter at the lower test levels on some equipment but not all. There was an order of magnitude in the relay chatter threshold over the range of equipment tested. Breaker trip resulted in many tests but usually at higher acceleration levels than relay chatter.

The relay chatter and breaker trip test results were, unfortunately, not completely logical. Frequently, functional failures would occur at one test level but not at twice that level. If the test results on a particular item of equipment were more logical, i.e., the failure rate increased with acceleration level, cumulative distribution functions (fragility curves) could be derived directly from the test data. Unfortunately, this was not always the case, and insufficient data were available for any one generic category of equipment to average out the spurious behavior and result in a well-defined cumulative distribution function. Since the failure modes of relay chatter and breaker trip were common to several generic categories of equipment, it was decided to combine all test data to increase the data base and result in more representative cumulative distribution functions for failure modes common to several generic categories of equipment. This is considered to be a reasonable evaluation of generic classes of off-the-shelf equipment that could have been installed in any nuclear power plant constructured in the same time frame as Zion.

Fragility relationships for permanent damage failure modes were also developed for individual generic categories of equipment. Three failure modes were then available for each generic category of electrical and control equipment, relay chatter, breaker trip and structural failure.

In applying the Corps of Engineers test results to develop generic fragility relationships for electrical and control equipment by failure modes, several assumptions were made regarding the equipment behavior when subjected to increasing levels of shock. First, it must be kept in mind that the equipment was subjected to predetermined levels of shock spectra and the percentage of component failure for different failure modes was observed for each shock spectrum level. It should also be borne in mind that, in most cases, permanent damage did not occur and that higher test levels could be achieved on the same equipment. Further, the test shock spectra were usually flat over a wide frequency range of interest so that spectral acceleration at the estimated fundamental frequency of the equipment is the fragility parameter of interest.

The percentage of component failures observed at each shock test level should not be confused with unconditional probabilities of failure. These failure rates may be interpreted as conditional probabilities of failure given that the equipment was operable up to that level of input acceleration. The unconditional probabilities of failure may then be computed by introducing the idea of a "hazard" or "risk" function. If f(x) is the Probability Density Function (PDF) of failure at acceleration level x, and $F(x) = \int_0^x f(\xi)d\xi$ is the Cumulative Distribution Function (CDF) of failure, then the risk (hazard) function is

$$\lambda(x) = \frac{f(x)}{1-F(x)} \qquad (4\text{-}10)$$

and inversely

$$F(x) = 1-\exp\left[-\int_0^x \lambda(\xi)d\xi\right] \qquad (4\text{-}11)$$

Clearly, $\lambda(x)dx$ is the probability of failure in the interval x to x+dx, given that the equipment is operable up to level x. Consequently, the percentages of failure at different input acceleration levels observed for each equipment define the shape of the hazard function for that equipment and the mode of failure which is being considered. For example, Figure 4-5 shows the hazard function for a particular equipment item. In order to estimate absolute values of the hazard function, the following approximate method is used:

For low values of input spectral acceleration, Equation 4-11 may be written as:

$$F(x) = \int_0^x \lambda(\xi)d\xi \qquad (4\text{-}12)$$

where the exponential on the right hand side of Equation 4-11 is expanded and only the linear term is used. Therefore, for low values of input acceleration, the conditional and the unconditional probabilities of failure are expected to be nearly equal. By using the percentage of failure at the lowest test level as F(x) in Equation 4-12 the absolute value of the hazard function is determined. Next, Equation 4-11 is used to compute the CDF of failure at different acceleration levels. Figure 4-6 shows the CDF of failure for the hazard function depicted in Figure 4-5.

Once the CDF's of failure for all items of equipment tested have been computed, they are simply averaged to compute the final CDF of failure for a given type of equipment failure mode.

A computer routine was developed to integrate the hazard functions to result in cumulative distribution functions for each equipment item tested and to arithemetically average the CDF's of like failure modes for all items tested. The individual hazard functions and resulting CDF's are tabulated in Appendix B.

The CDF's for each failure mode do not fit any specific probabilistic distribution and must, therefore, be treated in much the same manner as expert opinion from the SSMRP expert opinion questionnaire. Since only normal or lognormal distributions on fragility and response can be utilized in Phase I of the SSMRP, the test data based CDF's must be best fit to a normal or lognormal distribution. The expert opinion questionnaire asked for the 10%, 50% and 90% probability of failure fragility levels and normal and lognormal CDF's were fit through these three points. The same procedure was likewise used in defining the test data based CDF's in terms of normal and lognormal distributions.

The resulting CDF's and the lognormal least squares curve fits for relay chatter and breaker trip are shown in Figures 4-7 and 4-8. Figure 4-9 is the fragility curve and lognormal least squares curve fit for structural failure of electrical and control equipment.

Table 4-7 tabulates the results of the best normal and lognormal curve fits for the CDF's derived from test data.

The CDF's for relay chatter and breaker trip were curve fit for the 10%, 50% and 90% frequency of failure points. The derived structural failure CDF did not extend to a sufficiently high frequency of failure and was fit at the 35%, 50% and 65% frequency of failure points.

Note from Table 4-7 that the least squares curve fit for a normal distribution results in unrealistic fragility descriptions in the lower tail. The fragility is obviously not normally distributed and use of the best fit normal distribution is not recommended. The lognormal distribution appears to fit reasonably well within the 10% to 90% frequency of failure bounds.

4.3.8.4 Separation of Variability into Randomness and Uncertainty

In any fragility description, the variability in capacity can be attributed to random variability that is inherent in material properties, manufacturing tolerances and manufacturing processes. If all information regarding the variables that affect fragility of a product are known, there is still a random distribution and a random combination of the variables that influences the overall failure point. In deriving fragility descriptions of equipment by generic categories, a great deal of uncertainty is inherent since specific details of component construction, etc., are not addressed. Consequently, the generic fragility description for equipment, developed from test data, contain a large amount of uncertainty. Expression of the randomness and uncertainty in fragility descriptions was discussed in detail in Chapter 2.

Because of the generic treatment of equipment test data, there can be no mathematical derivation of the random and uncertainty portions of the fragility. Instead, engineering judgment must be used to separate out the random and uncertainty portions of the data. Guidelines can be developed from previous analytical derivations of fragility where material properties, ductility and uncertainty in failure modes were quantified for both structural and functional failures. For convenience, the lognormal distribution fragility descriptions are used to quantify the random and uncertainty portions of the failure modes.

For structural failure modes, the material properties, ductility and failure mode random variabilities ranged from 0.14 to 0.21 where these numbers represent logarithmic standard deviations. The uncertainty was almost always higher representing uncertainty in the actual material yield strength, system ductility, derivation of the ductility factor (given a ductility), uncertainty in the loading distribution and resulting failure mode.

For active equipment that fails in a functional manner, it is estimated that the random variability would be the same order of magnitude as for structural type failures. The largest contributor to variability would be uncertainty in the expected response due to the generic treatment of equipment manufactured by different firms and containing different components.

Estimates were made of the random and uncertainty portions of the variability in fragility and are tabulated in Table 4-2, which is a summary of all fragility descriptions.

TABLE 4-1
PIPE FITTINGS LOAD SCALE FACTORS

SIZE	SCHEDULE	MATERIAL	TEMPERATURE °F	UNREINFORCED* BRANCHES		ELBOWS	MITERS	STRAIGHT PIPE	BUTT WELDS	REINFORCED BRANCHES	
				F_{PR}	F_{PB}					F_{PR}	F_{PB}
1/2"	160	Stainless Steel	300° (D)	NA	NA	492	NA	298	480	NA	NA
3/4"	160	Stainless Steel	300° (D)	NA	NA	259	NA	157	254	NA	NA
1"	160	Stainless Steel	300° (D)	NA	NA	138	NA	83.5	135	NA	NA
2"	160	Stainless Steel	300° (D)	NA	NA	27.7	NA	43.5	27.0	NA	NA
2"	40	Stainless Steel	500° (D)	NA	NA	107	NA	37.5	60.4	NA	NA
3"	160	Carbon Steel	Ambient	NA	NA	4.8	NA	3.83	6.19	NA	NA
3"	160	Carbon Steel	140° (D)	NA	NA	4.93	NA	3.96	6.39	NA	NA
3"	160	Stainless Steel	300° (D)	NA	NA	9.85	NA	5.95	9.62	NA	NA
3"	160	Carbon Steel	556° (D)	NA	NA	6.24	NA	4.99	8.05	NA	NA
3"x3"x1/2"	160	Stainless Steel	300° (D)	9.62	480	NA	NA	NA	NA	9.62	480
3"x3"x3/4"	160	Stainless Steel	300° (D)	9.62	254	NA	NA	NA	NA	9.62	254
3"x3"x2"	160	Stainless Steel	300° (D)	10.0	27.0	NA	NA	NA	NA	9.62	27.0
3"x3"x3"	160	Stainless Steel	300° (D)	10.0	10.0	NA	NA	NA	NA	9.62	9.62
4"	40s	Stainless Steel	200° (D)	NA	NA	15.81	NA	5.12	8.25	NA	NA
4"	40s	Stainless Steel	300° (D)	NA	NA	17.65	NA	5.69	9.19	NA	NA
4"	40s	Stainless Steel	500° (D)	NA	NA	20.54	NA	6.60	10.63	NA	NA
4"	120	Carbon Steel	140° (D)	NA	NA	3.35	NA	2.26	3.63	NA	NA
4"	120	Stainless Steel	300° (D)	NA	NA	6.47	NA	3.27	5.27	NA	NA
4"	120	Stainless Steel	535°	NA	NA	7.72	NA	3.90	6.31	NA	NA
4"	160	Stainless Steel	300° (D)	NA	NA	4.87	NA	2.83	4.57	NA	NA
4"	160	Stainless Steel	535°	NA	NA	5.97	NA	3.47	5.60	NA	NA
4"x4"x3/4"	160	Stainless Steel	300° (D)	4.57	254	NA	NA	NA	NA	4.57	254
4"x4"x1"	160	Stainless Steel	300° (D)	4.57	135	NA	NA	NA	NA	4.57	135
4"x4"x2"	160	Stainless Steel	300° (D)	5.15	27.0	NA	NA	NA	NA	4.57	27.0
4"x4"x3"	160	Stainless Steel	300° (D)	5.15	9.64	NA	NA	NA	NA	4.57	9.62
4"x4"x4"	40s	Stainless Steel	500° (D)	21.0	21.0	NA	NA	NA	NA	10.63	10.63
4"x4"x4"	120	Carbon Steel	140° (D)	4.74	4.74	NA	NA	NA	NA	3.63	3.63
4"x4"x4"	120	Stainless Steel	300° (D)	6.72	6.72	NA	NA	NA	NA	5.27	5.27
4"x4"x4"	120	Stainless Steel	535° (D)	8.21	8.21	NA	NA	NA	NA	6.31	6.31
6"	120	Carbon Steel	Ambient	NA	NA	1.27	NA	0.76	1.24	NA	NA
6"	40	Carbon Steel	Ambient	NA	NA	3.77	NA	1.40	2.26	NA	NA
6"	120	Carbon Steel	140° (D)	NA	NA	1.30	NA	0.791	1.27	NA	NA
6"	160	Carbon Steel	Ambient	NA	NA	0.86	NA	0.63	1.0	NA	NA
6"x6"x3"	160	Carbon Steel	Ambient	1.22	6.19	NA	NA	NA	NA	1.0	6.19
6"x6"x4"	120	Carbon Steel	140° (D)	1.85	8.21	NA	NA	NA	NA	1.27	3.63
6"x6"x6"	120	Carbon Steel	Ambient	1.28	1.28	NA	NA	NA	NA	1.0	1.0

TABLE 4-1
PIPE FITTINGS LOAD SCALE FACTORS (Continued)

SIZE	SCHEDULE	MATERIAL	TEMPERATURE °F	UNREINFORCED* BRANCHES		ELBOWS	MITERS	STRAIGHT PIPE	BUTT WELDS	REINFORCED BRANCHES	
				F_{PR}	F_{PB}					F_{PR}	F_{PB}
18"	SW	Carbon Steel	Ambient	NA	NA	0.593	NA	0.135	0.217	NA	NA
18"	SW	Stainless Steel	200° (D)	NA	NA	1.11	NA	0.189	0.304	NA	NA
18"	SW	Stainless Steel	300° (D)	NA	NA	1.24	NA	0.209	0.339	NA	NA
18"	SW	Stainless Steel	500° (D)	NA	NA	1.43	NA	0.244	0.394	NA	NA
18"	40	Stainless Steel	400° (D)	NA	NA	0.671	NA	0.151	0.244	NA	NA
18"x18"x14"	40	Stainless Steel	400° (D)	0.711	1.17	NA	NA	NA	NA	0.244	0.515
20"	SW	Carbon Steel	Ambient	NA	NA	0.517	NA	0.110	0.176	NA	NA
20"	SW	Stainless Steel	200° (D)	NA	NA	0.966	NA	0.153	0.247	NA	NA
20"	SW	Stainless Steel	300° (D)	NA	NA	1.07	NA	0.170	0.274	NA	NA
20"	SW	Stainless Steel	500° (D)	NA	NA	1.24	NA	0.198	0.318	NA	NA
20"	tn=.500	Carbon Steel	Ambient	NA	NA	0.317	NA	0.083	0.134	NA	NA
24"	SW	Carbon Steel	Ambient	NA	NA	0.403	NA	0.075	0.122	NA	NA
27 1/2"	tn=2.38"	Stainless Steel	535°	NA	NA	0.032	NA	0.013	0.021	NA	NA
271/2"x271/2"x4"	tr=2.38" tb=0.438"	Stainless Steel	535°	0.021	6.32	NA	NA	NA	NA	0.021	5.60
271/2"x271/2"x8"	tr=2.38" tb=0.812"	Stainless Steel	535°	0.021	0.92	NA	NA	NA	NA	0.021	0.87
271/2"x271/2"x10"	tr=2.38" tb=1.125"	Stainless Steel	535°	0.034	0.438	NA	NA	NA	NA	0.021	0.438
29"	tn=2.50"	Stainless Steel	595°	NA	NA	0.029	NA	0.012	0.019	NA	NA
29"x29"x8"	tr=2.50" tb=0.812"	Stainless Steel	595°	0.0199	0.949	NA	NA	NA	NA	0.019	0.91
29"x29"x14"	tr=2.50" tb=1.406"	Stainless Steel	595°	0.0302	0.212	NA	NA	NA	NA	0.019	0.212
30"	tn=0.500"	Carbon Steel	Ambient	NA	NA	0.184	NA	0.036	0.058	NA	NA
30"x30"x20"	tr=0.500" tb=.375	Carbon Steel	Ambient	0.261	0.589	NA	NA	NA	NA	0.058	0.176
31"	tn=2.66"	Stainless Steel	530°	NA	NA	0.023	NA	0.0093	0.015	NA	NA
36"	tn=0.500"	Carbon Steel	Ambient	NA	NA	NA	0.255	0.025	0.040	NA	NA
36"x36"x36"	tn=0.500"	Carbon Steel	Ambient	0.203	0.203	NA	NA	NA	NA	NA	NA
48"	tn=0.625"	Carbon Steel	Ambient	NA	NA	NA	0.12	0.014	0.023	NA	NA
48"x48"x 20"	t=0.625	Carbon Steel	Ambient	0.0957	0.557	NA	NA	NA	NA	NA	NA
48"x48"x 30"	tr=.625 tb=.500	Carbon Steel	Ambient	0.0957	0.247	NA	NA	NA	NA	NA	NA
48"x48"x 48"	tr=.625 tb=.500	Carbon Steel	Ambient	0.0957	0.0957	NA	NA	NA	NA	NA	NA

* F_{PR}=Scale factor for run
F_{PB}=Scale factor for branch

TABLE 4-1
PIPE FITTINGS LOAD SCALE FACTORS (Continued)

SIZE	SCHEDULE	MATERIAL	TEMPERATURE °F	UNREINFORCED* BRANCHES		ELBOWS	MITERS	STRAIGHT PIPE	BUTT WELDS	REINFORCED BRANCHES	
				F_{PR}	F_{PB}					F_{PR}	F_{PB}
8"	40	Carbon Steel	Ambient	NA	NA	2.09	NA	0.71	1.15	NA	NA
8"	40s	Stainless Steel	200° (D)	NA	NA	3.92	NA	0.993	1.60	NA	NA
8"	40s	Stainless Steel	300° (D)	NA	NA	4.36	NA	1.11	1.78	NA	NA
8"	40s	Stainless Steel	350° (D)	NA	NA	4.47	NA	1.13	1.73	NA	NA
8"	40s	Stainless Steel	400° (D)	NA	NA	4.58	NA	1.16	1.87	NA	NA
8"	40s	Stainless Steel	500° (D)	NA	NA	5.04	NA	1.28	2.05	NA	NA
8"	140	Stainless Steel	535° (D)	NA	NA	1.16	NA	0.571	0.919	NA	NA
8"	160	Stainless Steel	535°	NA	NA	0.99	NA	0.54	0.87	NA	NA
8"	160	Stainless Steel	595°	NA	NA	1.03	NA	0.56	0.91	NA	NA
8"x8"x2"	40s	Stainless Steel	500° (D)	2.05	72.4	NA	NA	NA	NA	2.05	60.4
8"x8"x4"	40s	Stainless Steel	500° (D)	5.2	19.7	NA	NA	NA	NA	2.05	10.63
8"x8"x8"	40s	Stainless Steel	400° (D)	4.84	4.84	NA	NA	NA	NA	1.87	1.87
8"x8"x8"	40s	Stainless Steel	500° (D)	5.2	5.2	NA	NA	NA	NA	2.05	2.05
10"	40	Carbon Steel	Ambient	NA	NA	1.26	2.21	0.401	0.647	NA	NA
10"	40s	Stainless Steel	400° (D)	NA	NA	2.74	NA	0.654	1.05	NA	NA
10"	160	Stainless Steel	535° (D)	NA	NA	0.510	NA	0.272	0.438	NA	NA
10"x10"x8"	40s	Stainless Steel	400° (D)	2.89	4.54	NA	NA	NA	NA	1.05	1.87
10"x10"x10"	40s	Stainless Steel	400° (D)	2.89	2.89	NA	NA	NA	NA	1.05	1.05
12"	SW	Carbon Steel	Ambient	NA	NA	0.951	NA	0.274	0.441	NA	NA
12"	40s	Stainless Steel	200° (D)	NA	NA	1.78	NA	0.384	0.620	NA	NA
12"	40s	Stainless Steel	300° (D)	NA	NA	1.98	NA	0.426	0.688	NA	NA
12"	40s	Stainless Steel	500° (D)	NA	NA	2.30	NA	0.495	0.799	NA	NA
12"	40	Stainless Steel	400° (D)	NA	NA	1.83	NA	0.416	0.671	NA	NA
12"x12"x8"	40	Stainless Steel	400° (D)	1.92	4.27	NA	NA	NA	NA	0.67	1.97
12"x12"x12"x12"	40	Stainless Steel	400° (D)	1.92	1.92	NA	NA	NA	NA	0.67	[illegible]
14"	tn=0.375	Carbon Steel	Ambient	NA	NA	0.837	1.47	0.226	0.365	NA	NA
14"	40	Carbon Steel	Ambient	NA	NA	0.64	NA	0.197	0.31	NA	NA
14"	40	Stainless Steel	400° (D)	NA	NA	1.42	NA	0.319	0.515	NA	NA
14"	160	Stainless Steel	400° (D)	NA	NA	0.226	NA	0.115	0.186	NA	NA
14"	160	Stainless Steel	595° (D)	NA	NA	0.255	NA	0.131	0.211	NA	NA
14"x14"x12"	40	Stainless Steel	400° (D)	1.51	1.81	NA	NA	NA	NA	.515	0.671
14"x14"x14"	tn=0.375	Carbon Steel	Ambient	1.18	1.18	NA	NA	NA	NA	0.365	0.365
14"x14"x14"	40	Carbon Steel	Ambient	1.02	1.02	NA	NA	NA	NA	0.31	0.31
14"x14"x14"	160	Stainless Steel	400° (D)	0.237	0.237	NA	NA	NA	NA	0.186	0.186
16"	120	Carbon Steel	140° (D)	NA	NA	0.109	NA	0.061	0.099	NA	NA
16"	120	Carbon Steel	556° (D)	NA	NA	0.137	NA	0.077	0.124	NA	NA
16"x16"x3"	Run=120 Branch=160	Carbon Steel	556° (D)	0.124	8.05	NA	NA	NA	NA	0.124	8.05

TABLE 4-2 FRAGILITY DESCRIPTIONS

GENERIC CATETORY	SPECIFIC COMPONENT	FAILURE MODE	FUNDAMENTAL FREQUENCY Hz	FRAGILITY PARAMETER	MEDIAN DAMPING, % OF CRITICAL	MEDIAN CAPACITY	LOGARITHMIC STD. DEVIATION			RANK OF SOURCE
							COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	
Reactor Coolant System Class 1 Vessels and Supports	Reactor Pressure Vessel	Fracture of RPV Outlet Nozzle Safe End	5 (NSSS System)	Moment (in-lbs)	NA	2.12×10^8 in-lbs	0.36	0.21	0.29	5
Reactor Coolant System Class 1 Vessels and Supports	Steam Generator	Support Column Failure	5 (NSSS System)	Spectral Acceleration	5	5.2 g	0.34	0.14	0.31	5
Reactor Coolant System Class 1 Vessels and Supports	Pressurizer	Support Skirt Bolting	18-22	Spectral Acceleration	5	2.0 g	0.31	0.14	0.28	5
Reactor Coolant System Class 1 Vessels and Supports	Reactor Internals	Deformation of Guide Tube at Tube/Guide Plate Weld	5-15	Spectral Acceleration	5	2.75 g	0.24	0.14	0.19	5
Control Rods and Drives	Control Rod Housing	Control Rod Housing Deformation	6	Spectral Acceleration	5	6.0 g	0.24	0.14	0.19	5
Main Coolant Pumps	Reactor Coolant Pump	Support Column Failure	5 (NSSS System)	Spectral Acceleration	5	3.3 g	0.34	0.14	0.31	5
NSSS Piping	Generic Treatment	Fracture at RPV Outlet Nozzle	5 (NSSS System)	Moment (in-lbs)	NA	See Master Fragility Curve	0.37	0.21	0.30	4
Large Diameter Piping, 8" and Greater	Generic Treatment	Collapse	Variable	Moment (in-lbs)	NA	See Master Fragility Curve	0.37	0.21	0.30	4
Intermediate Diameter Piping, 2½"-8"	Generic Treatment	Collapse	Variable	Moment (in-lbs)	NA	See Master Fragility Curve	0.37	0.21	0.30	4

TABLE 4-2 FRAGILITY DESCRIPTIONS
(Continued)

GENERIC CATETORY	SPECIFIC COMPONENT	FAILURE MODE	FUNDAMENTAL FREQUENCY Hz	FRAGILITY PARAMETER	MEDIAN DAMPING, % OF CRITICAL	MEDIAN CAPACITY	LOGARITHMIC STD. DEVIATION COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	RANK OF SOURCE
Large Vertical Vessels and Heat Exchangers with Formed Heads	Generic Treatment	Support Failure or Nozzle Failure	Rigid	Zero Period Acceleration	NA	See Table 4-3	0.46	0.21	0.41	4
Large Vertical Vessels and Heat Exchangers with Formed Heads	Accumulator Tanks	Support Skirt Collapse	20.7	Spectral Acceleration	5	21.9 g	0.37	0.14	0.34	5
Large Vertical Vessels and Heat Exchangers with Formed Heads	RHR Heat Exchanger	Plastic Buckling of Shell	6.3	Spectral Acceleration	5	7.9 g	0.24	0.15	0.19	5
Large Flat Bottom Storage Tanks	Condensate Storage Tank	Buckling of Tank Wall at Base	Rigid Tank + Slosh	Zero Period Acceleration	NA	0.9 g	0.27	0.16	0.22	5
Large Flat Bottom Storage Tanks	Diesel Oil Storage Tank	Bending of Vertical Stiffener	Rigid Tank ~~+ Slosh~~	Zero Period Acceleration	NA	3.6 g	0.37	0.20	0.31	5
Large Horizontal Vessels and Heat Exchangers	Component Cooling Water Heat Exchanger	Support Failure	6.9	Spectral Acceleration	5	5.8 g	0.33	0.14	0.30	5
Large Horizontal Vessels and Heat Exchangers	Generic	Support Failure or Nozzle Failure	Rigid	Zero Period Acceleration	NA	See Table 4-3	0.46	0.21	0.41	4
Small-Medium Vessels and Heat Exchangers	Boron Injection Tank	Support Leg Failure	12.8	Spectral Acceleration	5	7.2 g	0.37	0.14	0.34	5
Small-Medium Vessels and Heat Exchangers	Generic	Support Failure or Nozzle Failure	Rigid	Zero Period Acceleration	NA	See Table 4-3	0.44	0.21	0.39	4
Buried Pipe	Service Water From Crib House	Buckling and Fracture	NA	Zero Period Acceleration	NA	1.4 g	0.42	0.17	0.39	5

TABLE 4-2 FRAGILITY DESCRIPTIONS
(Continued)

GENERIC CATETORY	SPECIFIC COMPONENT	FAILURE MODE	FUNDAMENTAL FREQUENCY Hz	FRAGILITY PARAMETER	MEDIAN DAMPING, % OF CRITICAL	MEDIAN CAPACITY	LOGARITHMIC STD. DEVIATION			RANK OF SOURCE
							COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	
Buried Pipe	Aux. Feedwater From Condensate Storage Tank	Buckling and Fracture	NA	Zero Period Acceleration	NA	1.4 g	0.42	0.17	0.39	5
Large Vertical Centrifugal Pumps with Motor Drive	Service Water Pumps	Bending of Pump Casing	7	Spectral Acceleration	5	3.7 g	0.21	0.14	0.15	4
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compressors	Residual Heat Removal Pump	Impeller Deflection	7	Spectral Acceleration	5	3.2	0.11	0.05	0.10	5
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compressors	Residual Heat Removal Pump	Mounting Bolt Failure	7	Spectral Acceleration	5	11.7	0.27	0.15	0.22	5
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compressors	Safety Injection Pump	Flange Bending	Rigid	Zero Period Acceleration	NA	3.4 g	0.35	0.14	0.32	5
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compressors	Safety Injection Pump	Shaft Binding	Rigid	Zero Period Acceleration	NA	5.25 g	0.17	0.14	0.10	5
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compressors	Centrifugal Charging Pump	Thrust Bearing Failure	Rigid	Zero Period Acceleration	NA	6.0 g	0.23	0.15	0.17	5
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compressors	Centrifugal Charging Pump	Shaft Deflection	Rigid	Zero Period Acceleration	NA	28.9 g	0.21	0.15	0.15	5

TABLE 4-2 FRAGILITY DESCRIPTIONS
(Continued)

GENERIC CATETORY	SPECIFIC COMPONENT	FAILURE MODE	FUNDAMENTAL FREQUENCY Hz	FRAGILITY PARAMETER	MEDIAN DAMPING, % OF CRITICAL	MEDIAN CAPACITY	LOGARITHMIC STD. DEVIATION COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	RANK OF SOURCE
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compessors	Generic Pumps & Compressors	Generic Function	Rigid	Zero Period Acceleration	NA	26 g	0.21	0.15	0.15	2
Large Motor Operated Valves	Generic	Functional Due to Distortion of Extended Operator Structure	Rigid	Piping Peak Acceleration	NA	6.3 g	0.6	0.2	0.57	4
Large Hydraulic & Air Operated Valves	Main Steam Isolation Valve	Oil Reservoir Hold Down Bolts	Rigid	Zero Period Acceleration	NA	7.3 g	0.3	0.14	0.26	5
Large Hydraulic & Air Operated Valves	Generic	Generic Function	Rigid	Zero Period Acceleration	NA	35 g	0.31	0.2	0.24	2
Large Check, Spring Relief & Manual Valves	Generic	Generic Function	Rigid	Piping Peak Acceleration	NA	38 g	0.32	0.20	0.25	2
Small Motor Operated Valves ≷8"	Generic	Functional Due to Distortion of Extended Operators	Rigid	Piping Peak Acceleration	NA	8.2 g	0.6	0.2	0.57	4
Small Miscellaneous Valves ≷8"	Generic	Generic Function	Rigid	Piping Peak Acceleration	NA	38 g	0.31	.20	.24	2
Emergency A.C. Power Units	Generator Control Panel	Relay Chatter	30	Spectral Acceleration	5	0.95 g	0.24	0.15	0.19	6
Emergency A.C. Power Units	Engine Control Panel	Failed Relay	11	Spectral Acceleration	5	2.0 g	0.25	0.15	0.20	6
Emergency A.C. Power Units	Engine Control Panel	Operspeed Shutdown Valve Trip	22	Spectral Acceleration	5	0.75 g	0.3	0.17	0.25	6

TABLE 4-2 FRAGILITY DESCRIPTIONS
(Continued)

GENERIC CATETORY	SPECIFIC COMPONENT	FAILURE MODE	FUNDAMENTAL FREQUENCY Hz	FRAGILITY PARAMETER	MEDIAN DAMPING, % OF CRITICAL	MEDIAN CAPACITY	LOGARITHMIC STD. DEVIATION COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	RANK OF SOURCE
Emergency A.C. Power Units	Engine & Generator Components	Structural	Rigid	Zero Period Acceleration	NA	>6.5 g	0.5	0.3	0.4	4
Emergency D.C. Power Units	Battery Rack	Anchor Bolts	8	Spectral Acceleration	5	12.5 g	0.3	0.21	0.24	5
Emergency D.C. Power Units	Batteries	Case Cracking & Plate Failure	8	Spectral Acceleration	5	4.2 g	0.16	0.1	0.12	6
Switch Gear	4160 & 480 Volt Units	Relay Chatter	5-10	Spectral Acceleration	5	2.07 g	1.46	0.5	1.37	6
Switch Gear	4160 & 480 Volt Units	Breaker Trip	5-10	Spectral Acceleration	5	7.7 g	0.73	0.4	0.61	6
Switch Gear	4260 & 480 Volt Units	Structural	5-10	Spectral Acceleration	5	14.6 g	0.8	0.4	0.69	6
Transformers	Generic	Structural	5-10	Spectral Acceleration	5	10.7 g	0.21	0.1	0.18	2
Local Instruments & Transmitters	Generic	Electrical Function	Rigid	Zero Period Acceleration	NA	37.8 g	0.32	0.2	0.25	6
Instrument Panels & Racks	Generic	Relay Chatter	5-10	Spectral Acceleration	5	2.07 g	1.46	0.5	1.37	6
Instrument Panels & Racks	Generic	Breaker Trip	5-10	Spectral Acceleration	5	7.7 g	0.73	0.4	0.61	6
Instrument Panels & Racks	Generic	Structural	5-10	Spectral Acceleration	5	14.6 g	0.8	0.4	0.69	6
Control Panels and Racks	Reactor Protection System	Functional-Electrical Manfunction	5-10	Spectral Acceleration	5	16 g	0.35	0.2	0.29	6
Control Panels and Racks	Generic	Relay Chatter	5-10	Spectral Acceleration	5	2.07 g	1.46	0.5	1.37	6

TABLE 4-2 FRAGILITY DESCRIPTIONS
(Continued)

GENERIC CATETORY	SPECIFIC COMPONENT	FAILURE MODE	FUNDAMENTAL FREQUENCY Hz	FRAGILITY PARAMETER	MEDIAN DAMPING, % OF CRITICAL	MEDIAN CAPACITY	LOGARITHMIC STD. DEVIATION			RANK OF SOURCE
							COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	
Control Panels and Racks	Generic	Breaker Trip	5-10	Spectral Acceleration	5	7.7 g	0.73	0.4	0.61	6
Control Panels and Racks	Generic	Structural	5-10	Spectral Acceleration	5	14.6 g	0.8	0.4	0.69	6
Relay Cabinets	Generic	Relay Chatter	5-10	Spectral Acceleration	5	2.07 g	1.46	0.5	1.37	6
Relay Cabinets	Generic	Relay Trip	5-10	Spectral Acceleration	5	7.7 g	0.73	0.4	0.61	6
Relay Cabinets	Generic	Structural	5-10	Spectral Acceleration	5	14.6 g	0.8	0.4	0.69	6
Motor Control Centers	Generic	Relay Chatter	5-10	Spectral Acceleration	5	2.07	1.46	0.5	1.37	6
Motor Control Centers	Generic	Breaker Trip	5-10	Spectral Acceleration	5	7.7 g	0.73	0.4	0.61	6
Motor Control Centers	Generic	Structural	5-10	Spectral Acceleration	5	14.6 g	0.8	0.4	0.69	6
Breaker Panels	Generic	Breaker Trip	5-10	Spectral Acceleration	5	7.7 g	0.73	0.4	0.61	6
Breaker Panels	Generic	Structural	5-10	Spectral Acceleration	5	14.6	0.8	0.4	0.69	6
Static Inverters	Zion Specific Static Inverter	Relay Trip	5-10	Spectral Acceleration	5	16 g	0.35	0.2	0.29	6
Air Conditioning & Air Handling Power Units	Containment Fan Coolers	Rubbing of Fan on Housing	4.3	Spectral Acceleration	5	2.0 g	0.23	0.15	0.17	5

TABLE 4-2 FRAGILITY DESCRIPTIONS
(Continued)

GENERIC CATETORY	SPECIFIC COMPONENT	FAILURE MODE	FUNDAMENTAL FREQUENCY Hz	FRAGILITY PARAMETER	MEDIAN DAMPING, % OF CRITICAL	MEDIAN CAPACITY	LOGARITHMIC STD. DEVIATION			RANK OF SOURCE
							COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	
Air Conditioning & Air Handling Power Units	Containment Fan Coolers	Rubbing of Motor Rotor on Housing	4.3	Spectral Acceleration	5	2.14 g	0.24	0.15	0.19	5
Air Conditioning & Air Handling Power Units	Generic	Generic Functions	10-30	Spectral Acceleration	5	9.5 g	0.24	0.15	0.19	6
Ducting	Generic	Structural Failure of Supports	Reference to ZPA	Zero Period Acceleration	NA	See Table 2-4	0.39	0.18	0.35	4
Cable Trays	Generic	Cable Support System	Fragility Referenced to ZPA	Zero Period Acceleration	NA	3 g	0.55	0.3	0.46	4
Off Site Power	Ceramic Insulators	Fracture of Insulators	Referenced to Ground ZPA	Peak Ground Acceleration	NA	0.2 g	0.32	0.20	0.25	4

Note: Rank of source based on following criteria

(a) Range is 1-6 with 1 being the least credible source.
(b) For generic equipment ranked 2, the information source is from short duration (2-5 sec) shock type tests and the failure modes are structural. The low ranking reflects the author's personal feeling that the energy content of the shock tests is not indicative of earthquake-type loading and that the fragility levels may be biased upward compared to actual fragilities of equipment subjected to a seismic input.
(c) A ranking of 4 reflects an analytical derivation of generic structural capacity of equipment designed to specific codes and standards or test data or historical earthquake data with limited documentation.
(d) A ranking of 5 reflects an analytical derivation of fragility, either structural or functional, for specific components for which design reports were reviewed or for which new analyses were conducted.
(e) A ranking of 6 reflects fragility descriptions developed from either fragility tests on plant specific or generic components or fragility descriptions developed from high shock level qualification tests utilizing the U.S. Corps of Engineers Pseudo-probabilistic methodology to develop fragility descriptions.

TABLE 4-3

FRAGILITY DESCRIPTION FOR VESSELS AND HEAT EXCHANGERS

Building and Floor Elevation	Design ZPA	Capacity ZPA	
		Small-Medium	Large
Crib House			
Elevation 552'	0.11	0.98	1.20
Elevation 594'	0.21	1.88	2.30
Auxiliary-Turbine Building			
Elevation 642'	0.25	2.24	2.74
Elevation 630'	0.20	1.79	2.19
Elevation 617'	0.17	1.52	1.86
Elevation 592'	0.12	1.07	1.32
Elevation 580'	0.10	0.90	1.10
Elevation 560'	0.08	0.72	0.88
Elevation 542'	0.08	0.72	0.88
Containment Building			
Elevation 617'	0.13	1.16	1.42
Elevation 590'	0.13	1.16	1.42
Elevation 582'	0.08	0.72	0.88
Elevation 568'	0.08	0.72	0.88
Outdoor Equipment	0.08	0.72	0.88
Variabiliby on Capacities		$\beta_C = 0.48$ $\beta_R = 0.21$ $\beta_U = 0.43$	$\beta_C = 0.49$ $\beta_R = 0.21$ $\beta_U = 0.44$

TABLE 4-4

FRAGILITY DESCRIPTION FOR DUCTING

Building and Floor Elevation	Design ZPA (DBE)	Capacity (ZPA)
Crib House		
Elevation 552'	0.2	0.82
Elevation 594'	0.22	0.91
Auxiliary-Turbine Building		
Elevation 642'	0.45	1.85
Elevation 630'	0.36	1.48
Elevation 617'	0.31	1.28
Elevation 592'	0.22	0.91
Elevation 580'	0.20	0.82
Elevation 560'	0.20	0.82
Elevation 542'	0.18	0.74
Containment Building		
Elevation 617'	0.24	0.99
Elevation 590'	0.20	0.82
Elevation 582'	0.17	0.70
Elevation 568'	0.17	0.70
Variability on Capacities		$\beta_C = 0.39$ $\beta_R = 0.18$ $\beta_U = 0.35$

TABLE 4-5

FRAGILITY DESCRIPTIONS DEVELOPED FROM CORPS OF ENGINEERS METHODOLOGY

Generic Category	Normal Distribution		Lognormal Distribution	
	Mean Spectral Acceleration, $\bar{S}_a$	Standard Deviation, σ	Median Spectral Acceleration, $\check{S}_a$	Logarithmic Standard Deviation, β
Large Hydraulic and Air Operated Valves	35.8	10.7	34.7	0.308
Large Check and Spring Relief Valves	39.8	12.0	38.5	0.311
Small Misc. Valves	39.8	12.0	38.5	0.311
Batteries	4.25	0.65	4.19	0.155
Transformers	10.8	2.25	10.7	0.210
Local Instruments	39.1	12.1	37.8	0.320
Air Conditioning and Air Handling Units (Structural Failure)	9.7	2.29	9.5	0.241
Air Conditioning and Air Handling Units (Fan Failure)	22.4	5.20	22.0	0.24
Pumps and Compressors	26.6	5.53	26.2	0.21

TABLE 4-6

SUMMARY OF f FACTORS

Generic Category	f_1 Upper	f_2 Upper	f_3 Upper	f_4 Upper	Upper Bound of Fragility $f_{1_U} \cdot f_{2_U} \cdot f_{3_U} \cdot f_{4_U}$	f_1 Lower	f_2 Lower	f_3 Lower	f_4 Lower	Lower Bound of Fragility $f_{1_L} \cdot f_{2_L} \cdot f_{3_L} \cdot f_{4_L}$
1. Large Hydraulic and Air Operated Valves	26.8	1.1	2.0	1.15	67.8	6.4	0.85	0.7	1.0	3.8
2. Large Check and Spring Relief Valves	30.0	1.1	2.0	1.15	75.9	6.0	0.85	0.7	1.0	3.6
3. Small Misc. Valves	30.0	1.1	2.0	1.15	75.9	6.0	0.85	0.7	1.0	3.6
4. Batteries	5.36	1.15	1.0	1.0	6.2	5.36	0.85	1.0	0.5	2.3
5. Transformers	13.34	1.10	1.2	1.0	17.6	6.63	0.85	0.8	0.9	4.1
6. Local Instruments	32.8	1.15	2.0	1.0	75.4	4.7	0.85	0.7	1.0	2.8
7. Air Conditioning and Air Handling Units (Structural Failure)	10.66	1.3	1.2	1.0	16.6	6.7	0.75	0.8	0.71	2.9
8. Air Conditioning and Air Handling Units (Fan Failure)	28.8	1.1	1.2	1.0	38.0	13.4	0.9	0.8	0.7	6.8
9. Pumps and Compressors	30.0	1.2	1.2	1.0	43.2	17.4	0.8	0.8	0.9	10.0

TABLE 4-7

FRAGILITY DESCRIPTIONS BY FAILURE MODE FOR ELECTRICAL AND CONTROL EQUIPMENT

FAILURE MODE	MEAN $\bar{A}$	STANDARD DEVIATION σ	MEDIAN $\check{A}$	LOGARITHMIC STANDARD DEVIATION β
CHATTER	4.72 g's	4.00 g's	2.074 g's	1.46
TRIP	10.85 g's	7.34 g's	7.97 g's	0.774
STRUCTURAL	15.0 g's	11.9 g's	14.6 g's	0.800

FIGURE 4-1

PIPING FRAGILITY DESCRIPTIONS

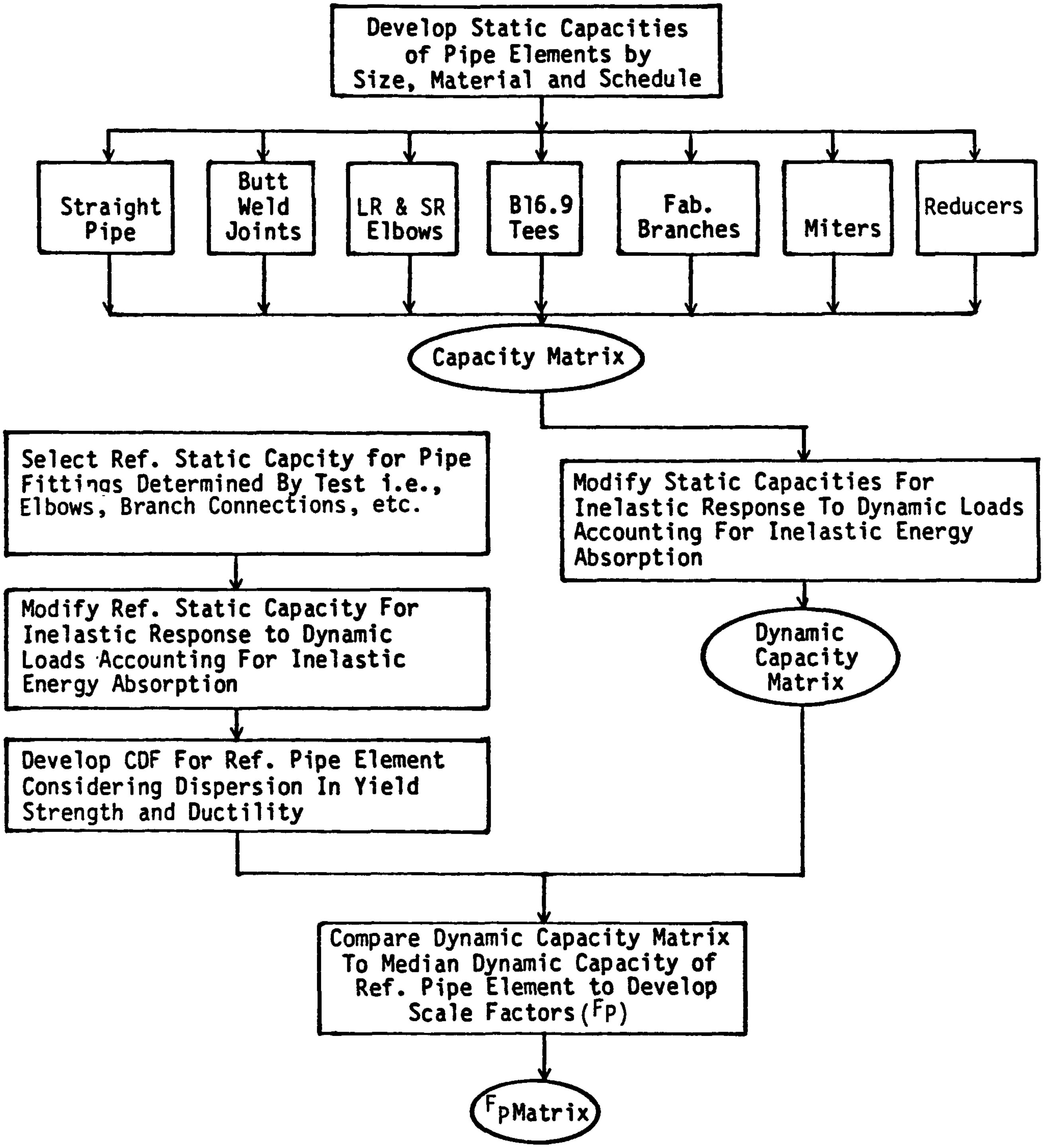


FIGURE 4-2

STATIC CAPACITIES OF PIPING COMPONENTS

STRAIGHT PIPE -	PLASTIC ANALYSIS INCLUDING STRAIN HARDENING AND STRAIN LIMIT.
BUTT WELDS - (INCLUDES REDUCERS AND TAPER TRANSITION)	PLASTIC ANALYSIS ASSUMING 1/2 THE STRAIN LIMIT OF WROUGHT MATERIAL.
UNREINFORCED FABRICATED BRANCH - CONNECTIONS AND TEES	$Mc = \frac{M_{Ref} \; i_{Ref} \, Z_c \, F_M \, F_T}{Z_{Ref} \; i_c}$
REINFORCED BRANCH - CONNECTIONS AND TEES	FRACTION OF BUTT WELD CAPACITY
ELBOWS AND BENDS	$Mc = \frac{M_{Ref} \; i_{Ref} \, Z_c \, F_M \, F_T}{Z_{Ref} \; i_c}$
MITER JOINTS -	$Mc = \frac{M_{Ref} \; i_{Ref} \, Z_c \, F_M \, F_T}{Z_{Ref} \; i_c}$

Mc = MOMENT CAPACITY OF COMPONENTS

M_{Ref} = MOMENT CAPACITY OF REFERENCE PIPE FITTING OF THE TYPE UNDER CONSIDERATION, (TEE, ELBOW, ETC.)

i = STRESS INTENSIFICATION FACTOR FROM ASME SECTION III SUBSECTION NC

Z = SECTION MODULUS $\pi r^2 t$

F_M = MATERIAL CORRECTION FACTOR

F_T = TEMPERATURE CORRECTION FACTOR

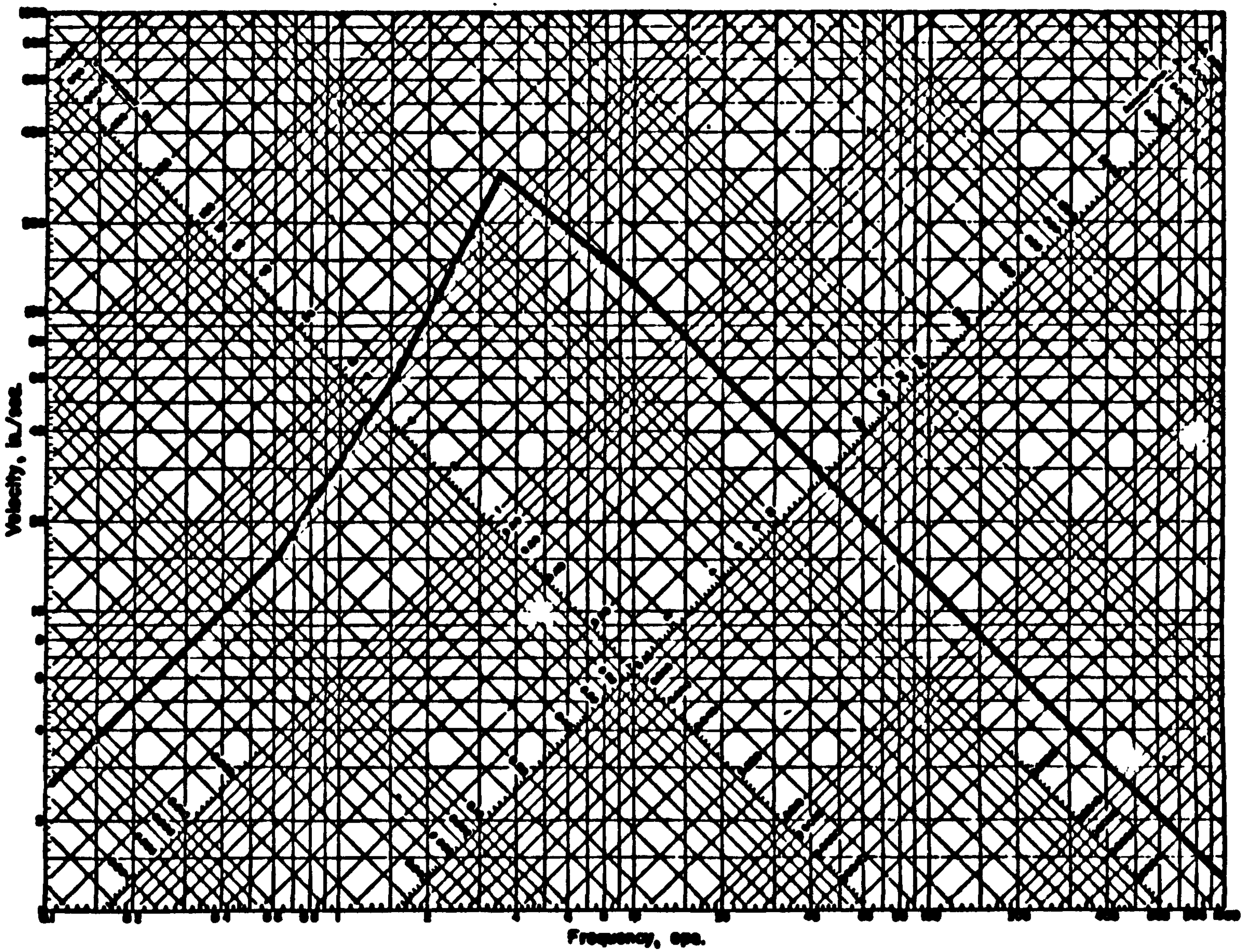


FIGURE 4-3. TYPICAL HARD MOUNTED SPECTRUM FOR MECHANICAL EQUIPMENT, HORIZONTAL SPECTRUM

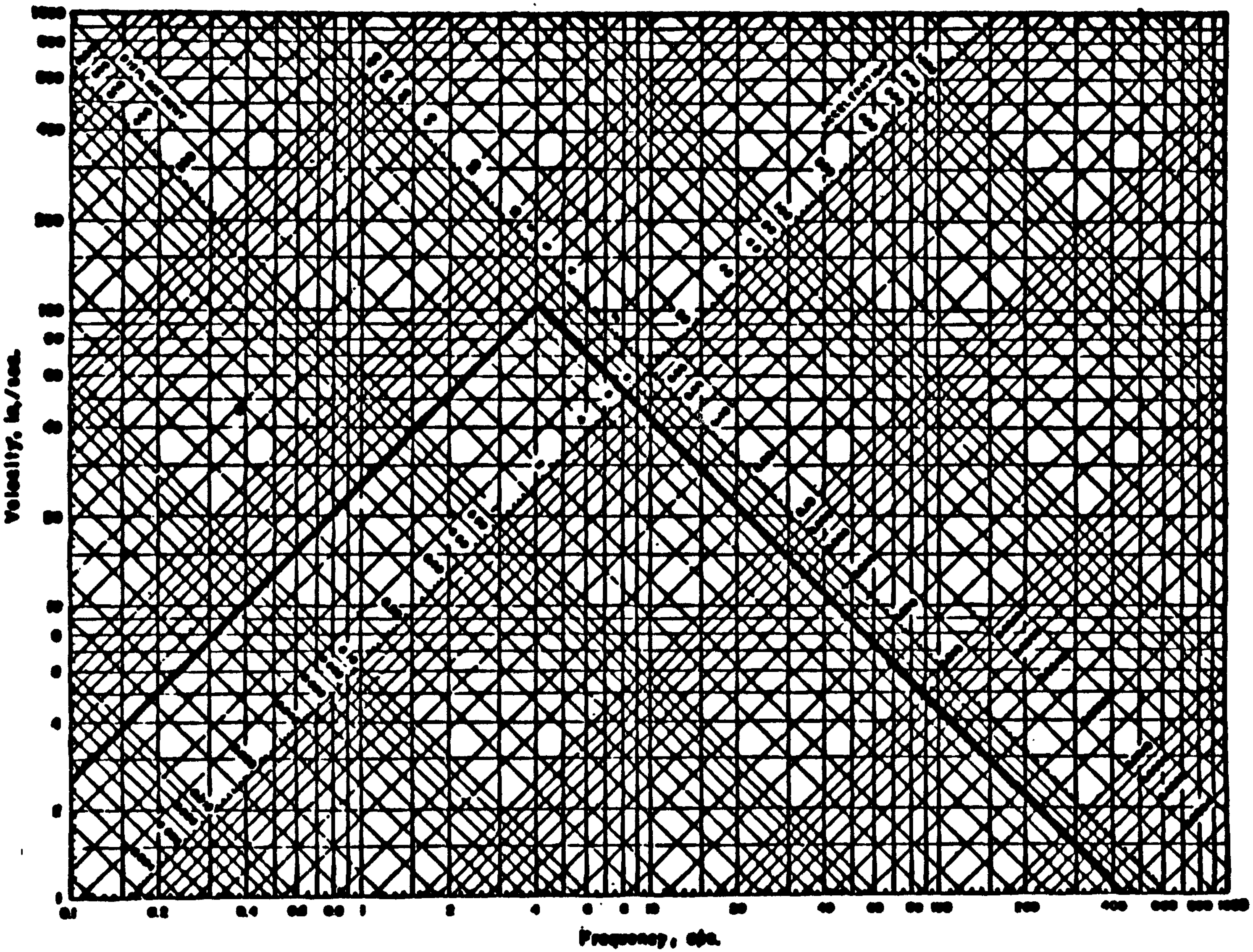


FIGURE 4-4. **TYPICAL SHOCK MOUNTED VERTICAL AND HORIZONTAL SHOCK SPECTRA FOR ELECTRICAL EQUIPMENT**

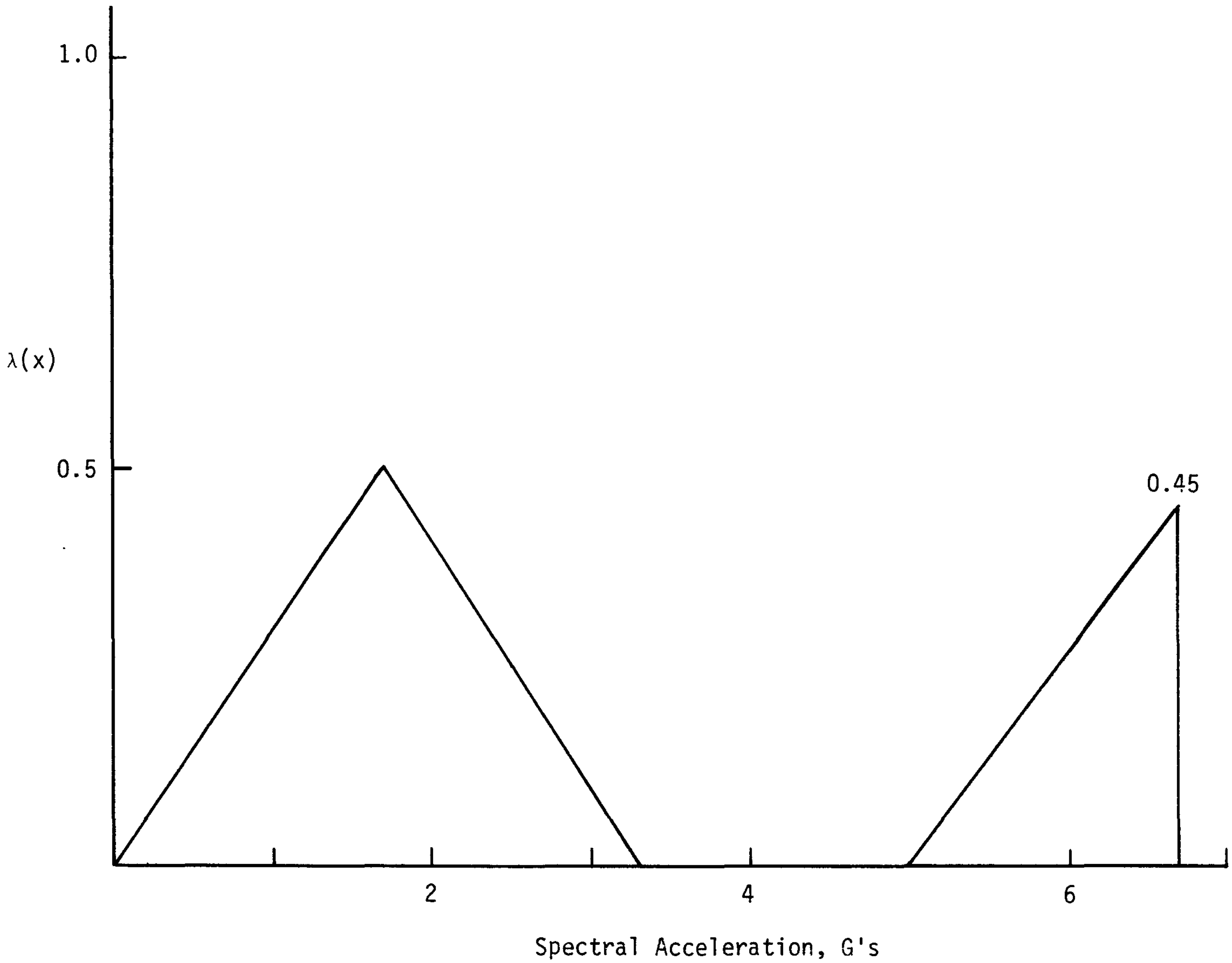


FIGURE 4-5. RISK FUNCTION

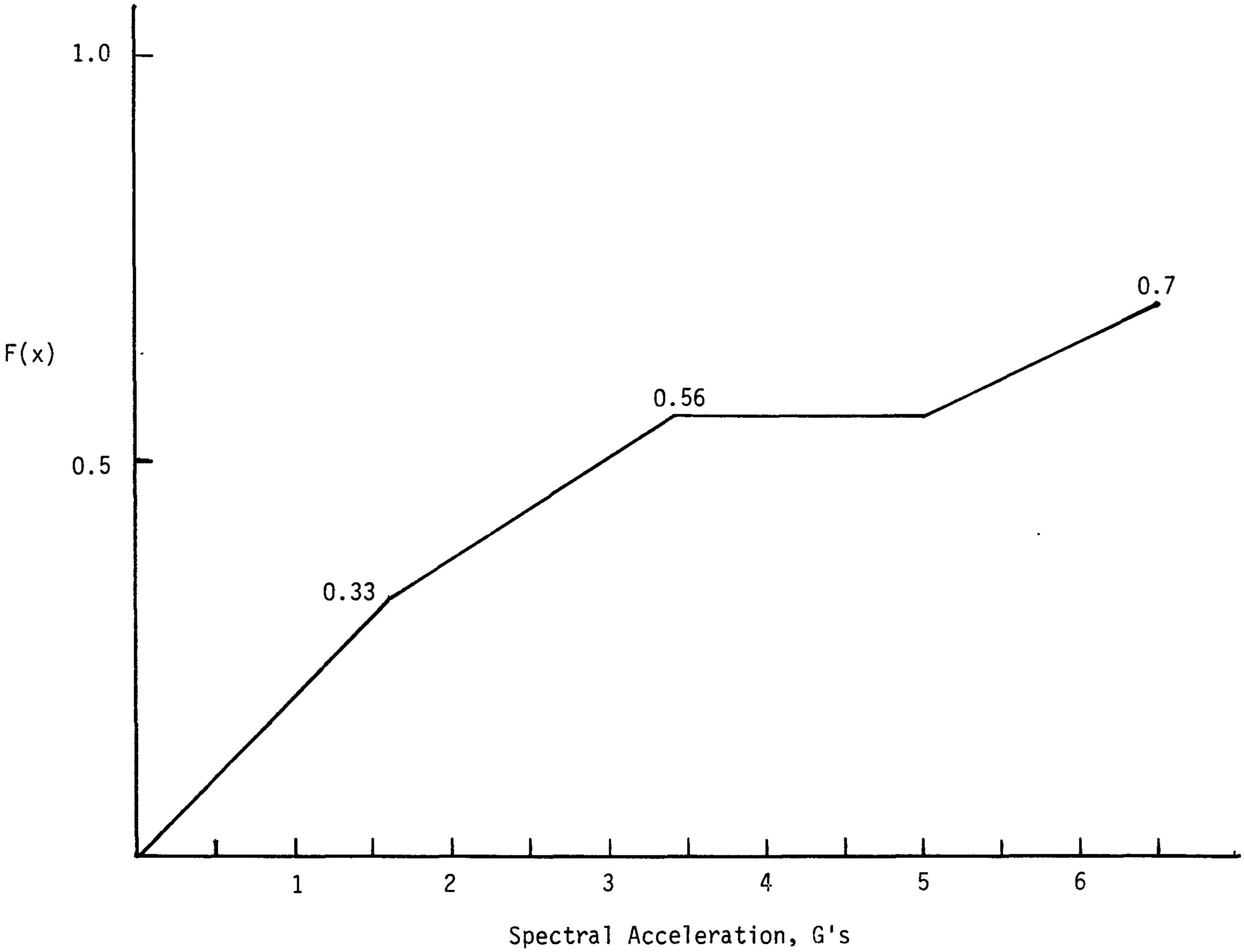


FIGURE 4-6. CUMULATIVE DISTRIBUTION FUNCTION

TOP→ OR LEFT↑

FIGURE 4-7. GENERIC ELECTRONIC ASSEMBLIES FRAGILITY CURVE WITH CHATTER FAILURE MODE

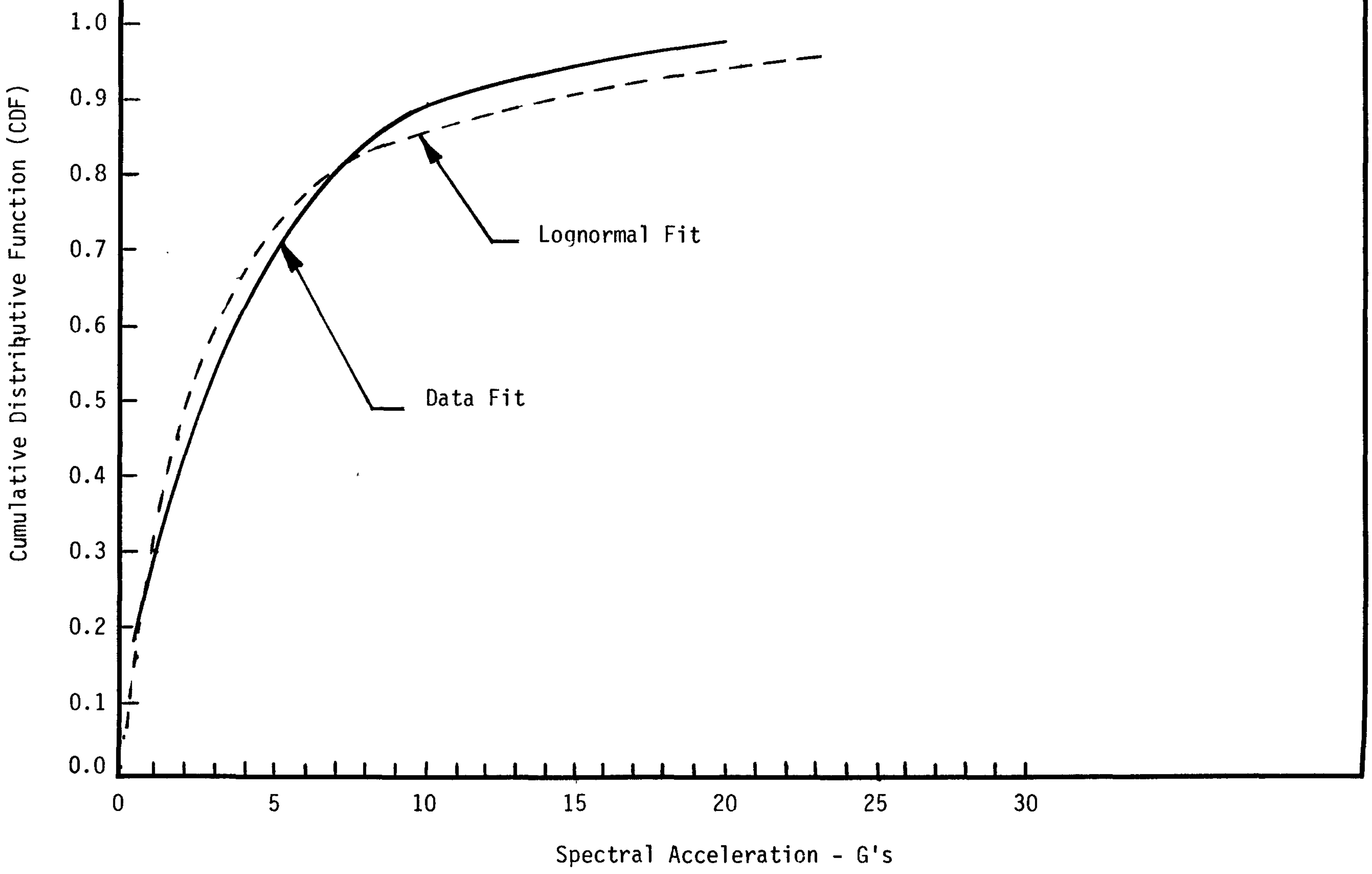
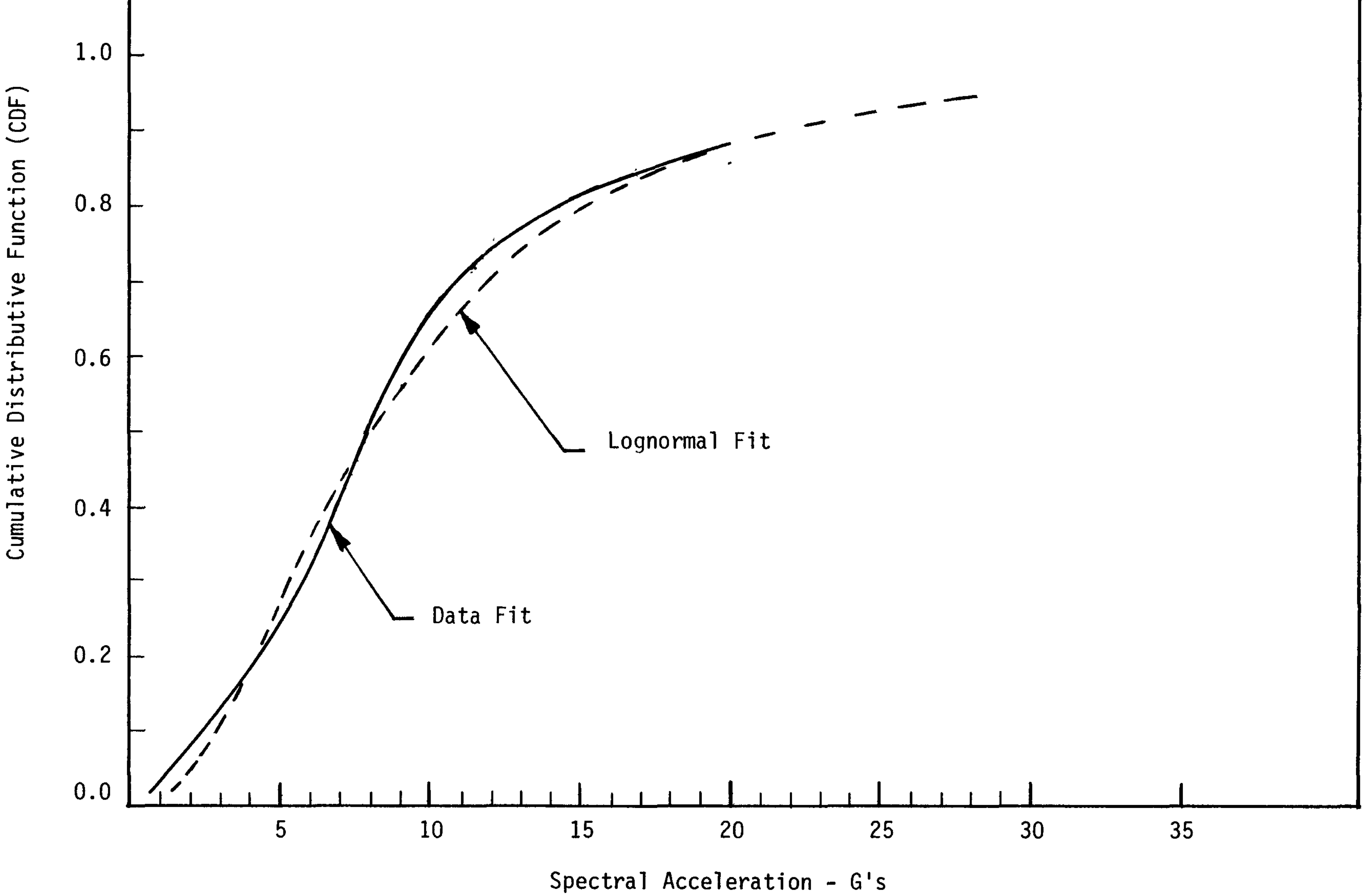


FIGURE 4-8. GENERIC ELECTRONIC ASSEMBLIES FRAGILITY CURVE WITH TRIP FAILURE MODE



TOP→ OR LEFT↑

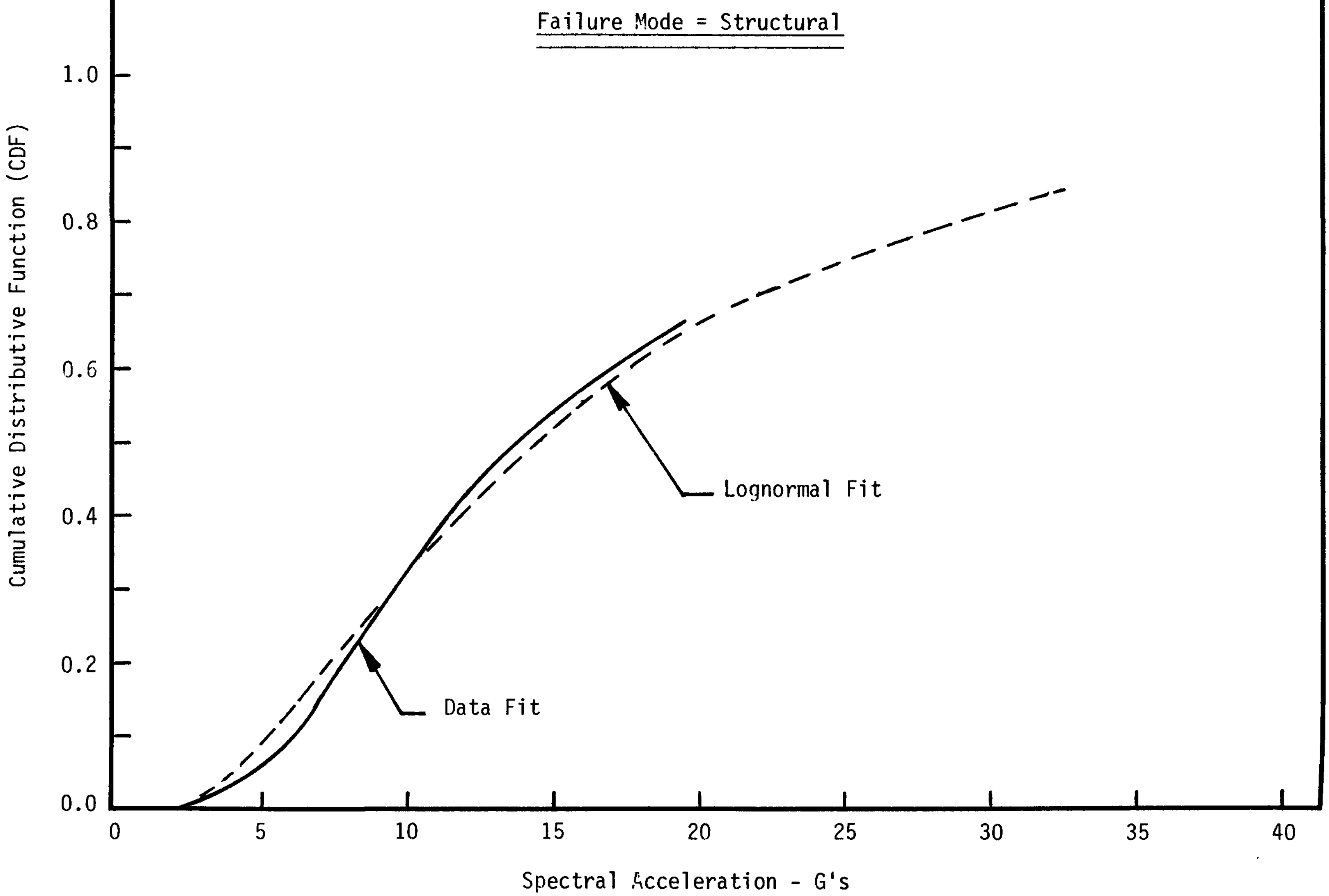


FIGURE 4-9. GENERIC ELECTRONIC ASSEMBLIES FRAGILITY CURVE WITH STRUCTURAL FAILURE MODE

5. RESPONSE FACTOR DEVELOPMENT

This chapter describes the development of response factors and their dispersion for plant specific and generic components. The term "response factor" is defined as the ratio of computed or synthesized test response to the actual response. In most designs, the calculations, or the parameters used in synthesizing tests, are biased on the conservative side and the response factor will, in general, be greater than 1.0. The response factor is not a deterministic value and is described in probabilistic terms. In the SSMRP, new mean or median centered responses of the structures and major NSSS equipment will be computed; thus, there should be no bias in defining floor spectra applicable to equipment. Also, when fragility parameters are specified, they will be keyed to median centered variables such that, in most instances, there will be no bias in the estimated equipment response. For instance, for acceleration sensitive components, the fragility parameter will be spectral acceleration at the best estimate of equipment frequency and for median damping. There is, however, a great deal of variability in response that must be addressed since the fragility descriptions contain only the variability associated with strength and ductility.

Studies documented in the literature, References 4 and 58, have attempted to identify sources of dispersion on response and to quantify these sources of dispersion. Reference 58 is a report prepared under the SSMRP program that discusses sources of response dispersion and generic ranges of the dispersion. Examples are also presented on calculations of specific response factors and their dispersion.

Dispersion in the response factors is made up of two parts. The first part is due to the underlying randomness of the parameters influencing the responses and the second part is due to the modelling uncertainty in estimating these parameters and the uncertainty in test simulation processes due to a lack of complete information or knowledge about the parameters. In the SSMRP study, these two sources of variability are kept separate. Variability in response is assumed to be longnormally distributed and the response factors and their variabilities are described in lognormal terms, the variabilities of the response factors being described as the logarithmic standard deviation about the median.

Chapter 2 presents a description of the lognormal distribution cumulative distribuion function and the physican meaning of the variability when separated into random and modelling uncertainty components. The random portion of the variability is denoted as β_R and the modelling uncertainty portion of the variability is denoted as β_U. A less descriptive estimate of variability in response can be represented by combining the random and modelling uncertainty variability. For a lognormal response distribution, the composite variability, β_C, is:

$$\beta_C = \sqrt{\beta_R^2 + \beta_U^2}$$

In deriving variability in response, it is often more convenient to derive or estimate the β_C value first and then separate the random and modelling uncertainty portions out. This is the approach taken in this chapter. For many variables that affect response, the variability may be predominantly random, predominantly modelling uncertainty or a combination of both.

Reference 58 describes in detail the sources of conservatism and unconservatism and the variabilities in responses. In some instances, sources of variability can be quantified generically, but in most cases, as described in Reference 58, the response factors and their variabilities are plant and component specific. In deriving response factors and their variabilities for the SSMRP the following parameters are considered.

Qualification Method

Modelling Error

- Frequency
- Mode Shape

Damping

Modal Response Combination

Earthquake Component Combination

Note that the variability on response due to frequency and damping variability is strongly dependent on the applicable response spectrum. Since this work is being conducted in parallel with new response calculations, the original design spectra were necessarily used to estimate variabilities.

First, plant specific components, which are to be included in the Phase I risk modelling and for which qualification reports were reviewed, are addressed. Response factors and their dispersions for each component or group of components, due to the above variables, are derived from information in the qualification reports. Secondly, response factors for generic classes of components, whose fragility descriptions are derived from military shock test data, are derived. Thirdly, generic response factors and their dispersions are developed for components and systems whose responses will be recalculated in the SSMRP subsystem response program.

5.1 PLANT SPECIFIC COMPONENTS QUALIFIED BY ANALYSIS

Review of the available qualification data indicated that many of the plant specific qualifications were based upon the static analysis method. Typically, for these cases, an estimate of the fundamental frequency was made. Then, depending upon the frequency and the floor response spectra, a suitable spectral acceleration was selected, an equivalent static load was applied and a stress analysis was performed. The acceptance criteria were satisfaction of the stress requirements prescribed in the applicable codes and standards, or demonstrations that deflections were within functional limits. The static coefficient method was applied to both rigid and flexibile equipment.

In many cases, the components for which qualification reports were reviewed, and which will be included in the SSMRP Phase I risk model, were considered to be rigid. Therefore, there was less variability in the calculated response than for flexible components since many of the sources of variability in dynamic system response are not present in rigid structures.

Many of the NSSS components and engineered safety system components were qualified for seismic service via dynamic analyses. The response spectrum method was used for qualification of equipment by dynamic analysis.

Plant specific component response factor development falls into three categories: 1) flexible equipment qualified by dynamic analysis, 2) flexible equipment qualified by static analysis and 3) rigid equipment qualified by static analysis.

5.1.1 Flexible Components Qualified by Dynamic Analysis

The following equipment items are included in this category:

a. Reactor Pressure Vessel
b. Steam Generators and Supports
c. Reactor Coolant Pumps and Supports
d. Control Rod Drive Mechanisms
e. Reactor Internals
f. Containment Fan Coolers
g. RHR Pumps and Motors
h. Residual Heat Exchangers
i. Accumulator Tanks
j. Boron Injection Tanks
k. Component Cooling Heat Exchangers
l. Service Water Pumps

The response spectrum method was used for analysis of the above items. The worst horizontal plus the vertical direction responses were combined by the absolute sum method and individual modal responses were combined by the square-root-of-the-squares. Items (a) through (c) were included in a single system model along with the primary coolant piping. Other items were evaluated by treating each component as uncoupled and subjected to generic or plant specific floor spectra.

In order to avoid repetition of detail in deriving response factors for each individual component, a single example will be addressed in detail which is representative of the process. Response factors and their variabilities for each individual component were calculated by the same method as portrayed in the example and are tabulated in Table 5-1.

The service water pump is used an an example of the application of response factors and their variabilities to non-rigid dynamic systems. From documentation reviewed for the service water pump, it appeared that several iterations were made for qualification of the pump by analysis. The pump is a long column vertical pump which mounts in the crib house at elevation 594.5'. It is about 42 feet long and is supported laterally at elevations 579.5 feet and 564 feet. The final analysis submitted by the vendor treated the pump as a multi-supported beam with a concentrated mass at the lower end (elevation 552 feet) corresponding to the lumped mass of the pump. Very little detail was provided on pump masses and whether the mass of the displaced water was included in the frequency analysis. Therefore, several assumptions which increase the overall uncertainty were necessarily made in the derivation of the response distributions.

An examination of each of the sources of response variability was made. Computation of the corresponding response factors, random variabilities and modelling uncertainty variabilities were developed for the service water pumps as an example of the derivation process for the numerical values contained in Table 5-1.

5.1.1.1 Qualification Method

First, the method of qualification is considered. The qualification was done by the response spectrum method. One could say that the static coefficient method was used since only one predominant frequency was considered and a static stress analysis was performed using the spectral acceleration from the applicable response spectrum curve at the calculated fundamental frequency of the system. In either case, the basic method of analysis is considered to be median centered. Since the pump is actually a multi-degree-of-freedom system, a logarithmic standard deviation of 0.1, as suggested by Reference 58 is considered as the variability due to the qualification method. The variability is considered to be equally due to randomness in the parameters that make up the analysis process and modelling uncertainty in the mathematical solution of the response problem by spectral methods. The response factor for qualification method and its variabilities are:

$$F_{QM} = 1.0$$

$$\beta_{C_{QM}} = 0.1$$

$$\beta_{R_{QM}} = 0.07$$

$$\beta_{U_{QM}} = 0.07$$

5.1.1.2 Modelling Error

The modelling error factors for the service water pump are composed of two parts, error due to frequency and error due to mode shape.

5.1.1.2.1 Frequency - The fundamental frequency was calculated using a single-degree-of-freedom equivalent system, but appeared, from a review of the design calculations, to underestimate the fundamental frequency due to two factors:

1. The total pump mass was concentrated at the pump bowl at elevation 552 feet;

2. The lumping of the pump mass at the extreme lower end of the pump result in a cantilever beam of excessive length for purposes of determining the natural frequency.

The vendor calculated a first mode frequency of 4.3 Hz which corresponds to a 1.7g spectral acceleration for the DBE at 2 percent damping. Without constructing a dynamic model of the pump, some estimates of frequency correction were made, accounting for the above stated modelling errors. It is estimated that the fundamental frequency is on the order of 7 Hz with a possible error range of about $\pm$33 percent. Using this estimate of frequency and the design response spectrum, the modal response factor due to frequency error and its logarithmic standard deviation are:

$F_F = 0.75$ $\beta_F = 0.13$

However, in specifying the fragility parameter for the service water pump, if the estimated median frequency of 7 Hz is specified, the appropriate frequency response factor is 1.0. The variability of response due to frequency uncertainty is still present and, based on the shape of the design response spectrum, remains at 0.13. This is almost all modelling uncertainty. The response factor and variabilities for frequency effects are:

$F_F = 1.0$

$\beta_{C_F} = 0.13$

$\beta_{R_F} = 0.05$

$\beta_{U_F} = 0.12$

5.1.1.2.2 Mode Shape - A correction for mode shape error should also be made. From Reference 58, the modal response error and variability due to mode shape for a SDOF system are estimated to be:

$F_{MS} = 1.0 \qquad \beta_{MS} = 0.1$

The random and uncertainty portions of the variability on response due to mode shape are 0.05 and 0.09, respectively.

5.1.1.2.3 Combined Modelling Error - The combined contribution from modelling error is then:

$F_{ME} = 1.0 \qquad \beta_{C_{ME}} = 0.16$

$\beta_{R_{ME}} = 0.07 \qquad \beta_{U_{ME}} = 0.14$

5.1.1.3 Damping

If median damping, assumed to be about 5% for equipment responding to earthquakes above the DBE level, is specified as part of the fragility parameter, the response factor on damping is unity. Reference 58 suggests that the minus one logarithmic standard deviation on damping is about 3.5%. The effect on response depends upon the spectral shape and fundamental frequency of the equipment. Using the original design response spectrum and the estimated median frequency of 7 Hz, the variability due to damping can be computed as:

$$\beta_D = \ell n \frac{S_{a_{\xi = 3.5\%}}}{S_{a_{\xi = 5\%}}}$$

In this case, $\beta_D = 0.15$.

Response variability due to damping can be considered to be both due to randomness and due to uncertainty in the specific component damping values. The estimated contributions of each are:

$\beta_{R_D} = 0.1$ $\beta_{U_D} = 0.11$

5.1.1.4 Combination of Modes

The pump was treated as a SDOF system; therefore, combination of modes does not enter into the variability per se. However, there are higher modes in the pump which were neglected. Their influence is considered small on the critical bending moment at elevation 564 feet, but they do have some influence. Therefore, an estimate is made of the unconservatism and variability due to neglect of higher modes. Some simple hand calculations indicate that the higher modes would be beyond 30 Hz. An upper bound on added horizontal response would be the application of the ZPA to the single-degree-of-freedom response. This would have increased the computed median design response by 0.22g to 2.02g. Assuming that the range between 1.8 and 2.02g is one logarithmic standard deviation, the variability due to neglect of higher modes is computed to be 0.06, and the response factor is computed to be 0.94. The variability can be considered to be all modelling uncertainty due to the approximate solution obtained by neglecting the higher modes. Thus:

$F_{MC} = 0.94$ $\beta_{R_{MC}} = 0.0$

$\beta_{C_{MC}} = 0.06$ $\beta_{U_{MC}} = 0.06$

5.1.1.5 Combination of Earthquake Components

In the original design, resulting stresses were computed for one direction of horizontal spectral acceleration and for the vertical spectral acceleration. The stresses were combined by the absolute sum method and compared to allowable values. The vertical response was a small contributor to the total pump case stress and, as such, only the horizontal spectrum was of importance.

The service water pump fragility description is based upon a horizontal acceleration vector which could result from combined response to two horizontal directions of earthquake. Lawrence Livermore Laboratory, in computing structural responses and developing floor spectra to apply to equipment, will develop median centered spectra for three orthogonal directions. The fragility description is based upon the assumption that median centered vector sums of the three orthogonal spectral accelerations for a given frequency will be input into the risk model (SEISIM) and not the vector sum of the absolute value of the three orthogonal spectral accelerations. Since the vector input will be median centered, the response factor for earthquake component combination is unity. There is, however, a variability associated with the earthquake component combination. The vertical spectral acceleration is not a strong contributor to response of the pump so only the variability in response due to phasing of the two horizontal components is considered. For worst case phasing of two equal horizontal inputs the maximum vector is 1.414 times the worst case input. The other extreme is a no phasing or no orthogonal component case where the maximum vector is 1.0 times the worst case input. Both of these extremes are almost zero probability of occurrence cases and it is not practical to derive variability from extreme tail values. Reference 58 recommends that the coefficient of variation (approximate logarithmic standard deviation) for combination of earthquake components is about 0.15. Considering that only two directions are major contributors to the service water pump response, the logarithmic standard deviation on combination of earthquake components is estimated to be about 0.1. Earthquake component phasing is a purely random phenomena, thus;

$$\beta_{R_{ECC}} = 0.1$$

$$\beta_{U_{ECC}} = 0.0$$

5.1.1.6 Combined Response Factors and Variability for Service Water Pump

As described in Chapter 2, the combined response factor is the product of the individual response factors and the combined vriabilities are the square-root-of-the-sum-of-the-squares of the individual variabilities.

$F_R = 0.94$

$\beta_C = 0.27$

$\beta_R = 0.17$

$\beta_U = 0.21$

5.1.2 Flexible Components Qualified by Static Analysis

The pressurizer was the only plant specific component included in this study that is flexible and was qualified by static analysis. References 55 and 56 describe the seismic loading and stress analysis conducted for the pressurizer.

In the pressurizer support skirt and flange design report, Reference 56, static coefficients of 0.96g horizontal and 0.64g vertical were used for calculating stresses due to seismic excitation. Typical pressurizers of the type installed in Zion have a fundamental frequency of 18-22 Hz.

Since the equipment is flexible, response factors and variabilities in these factors must be developed in almost the same manner as demonstrated for the service water pump. In this case, however, since the first fundamental frequency for the pressurizer is higher than for the service water pump, the pressurizer will be considered to respond in a single mode, i.e., no other significant modes are present below the ZPA frequency.

5.1.2.1 Qualification Method

The pressurizer fragility description was based on the magnitude of the horizontal static coefficient of 0.96g. In developing the capacity factor, the failure mode of concern was the pressurizer support skirt bolting which experienced significant seismic stress due to overturning. The vertical component of earthquake has a much smaller effect on bolt stress and was ignored for purposes of developing a fragility description. It is felt that ignoring the vertical response does not affect the median response, in this case; thus, the response factor for qualification method is 1.0. A variability on this value is assigned to account for the fact that vertical acceleration has both a positive and negative effect on the median response factor. Since the vertical acceleration effect is considered small in comparison to the horizontal acceleration effect, the estimated coefficient of variations (approximate logarithmic standard deviation) in the response factor is 0.10. This is considered to be all uncertainty due to the fact that the response factor, estimated to be unity, was developed lacking access to detail on both vertical and horizontal response. In summary:

$$F_{QM} = 1.0$$

$$\beta C_{QM} = 0.1$$

$$\beta R_{QM} = 0.0$$

$$\beta U_{QM} = 0.1$$

5.1.2.2 Modelling Error

5.1.2.2.1 - Frequency - The natural frequencies for various pressurizer units range from approximately 18-22 Hz. 20 Hz was used as a median value for purposes of developing response factors. Reference 58 suggests that the coefficient of variation (approximate logarithmic standard deviation) on frequency computation is about 0.3 for the general case for complex equipment. For simple geometrics like the pressurizer the coefficient of variation is estimated to be on the order of 0.15. The effect on response depends upon the spectral shape and the frequency of interest. Using the 5% median damped DBE spectrum for the containment building at elevation 590', the ratio of response, for a -1β frequency to median response, is approximately 1.18 resulting in a logarithmic standard deviation for the frequency response factor of 0.16. The contribution due to randomness of material properties, member dimensions, etc., is estimated to be about β_{R_F} = 0.08. The more significant contributor is uncertainty regarding boundary conditions and modelling assumptions and is, β_{U_F} = 0.24.

The frequency analysis is considered to be median centered such that:

$$F_F = 1.0$$

5.1.2.2.2 - Mode Shape - It was assumed that there was only one significant mode of response within the range of frequency of the earthquake. The analysis for frequency and mode shape is considered to be median centered, thus:

$$F_{MS} = 1.0$$

Reference 58 suggests that the coefficient of variation (approximate logarithmic standard deviation) for mode shape for a single-degree-of-freedom system is about 0.1. This variability is more heavily influenced by modelling assumption than random variation of material properties and member sizes such that the estimated random and uncertainty variability are:

$$\beta_{R_{MS}} = 0.05$$

$$\beta_{U_{MS}} = 0.09$$

5.1.2.3 Damping

Median damping for the pressurizer is estimated to about 5% for earthquake levels above the DBE. Median damping will be specified with the pressurizer fragility parameters; consequently, the median response factor for damping is 1.0.

The minus one logarithmic standard deviation damping value is estimated, Reference 58, to be 3.5%. Thus, the logarithmic standard deviation on the response factor, due to damping, can be computed from:

$$\beta_D = \ln \frac{S_{a_{\xi = 3.5\%}}}{S_{a_{\xi = 5\%}}}$$

Using the original design response spectrum, the damping response factor logarithmic standard deviation is:

$$\beta_D = 0.07$$

This is considered to be about half random and half uncertainty such that:

$$\beta_{R_D} = 0.05$$

$$\beta_{U_D} = 0.05$$

5.1.2.4 - Mode Combination - In the case under consideration, there is only one mode of interest being considered; therefore, the response factor is 1.0 with variability equal to zero.

5.1.2.5 - Combination of Earthquake Components - The pressurizer, being a tall, vertical vessel, responds predominantly in two horizontal directions. The Zion criterion of combining response in the worst horizontal direction with response in the vertical direction by absolute summation ignores the additional horizontal component for this configuration. This is the same situation as described previously for the service water pump. The response input to SEISIM will be median centered and the response factor is unity. The variability on response, due to combination of earthquake components, will be the same as derived for the service water pump.

$F_{ECC} = 1.0$

$\beta_{C_{ECC}} = 0.1$

$\beta_{R_{ECC}} = 0.1$

$\beta_{U_{ECC}} = 0.0$

5.1.2.6 - Combined Response Factor and Variability - The combined values of all significant variables contributing to response of the pressurizer are:

$F_R = 1.0$

$\beta_C = 0.37$

$\beta_R = 0.20$

$\beta_U = 0.31$

5.1.3 Rigid Equipment Qualified by Analysis

Many of the qualification reports indicated that the equipment was rigid and qualification analysis was by the static coefficient method. Following is a discussion on the derivation of response factors and their dispersion for rigid equipment qualified by analysis.

5.1.3.1 Qualification Method

When equipment is rigid and the zero period acceleration of the applicable response spectrum is applied, the analysis method is considered to be median centered. The logarithmic standard deviation on response due to the method of analysis itself is considered to be very small and is estimated to be on the order of 0.05. This is considered to be random variability in the method itself as there can be very little uncertainty about the results of the static analysis for a given model, thus:

$$F_{QM} = 1.0$$

$$\beta_{R_{QM}} = 0.05$$

$$\beta_{U_{QM}} = 0.0$$

5.1.3.2 Modelling Error

Modelling error for static analyses is due primarily to the representation of the component behavior as a simplified mathematical model. Most of the analyses were conducted by simple hand calculation methods. There was no intended or inherent bias evident in modelling such that modelling is considered to be median centered. There is, however, variability in computed stress response due to the uncertainty in representing complex structures as simple mathematical models that can be solved by hand. The logarithmic standard deviation of response due to modelling error is estimated to be about 0.15. This is analogous to the mode shape variability discussed in Reference 58. There is no contribution due to frequency error since the response spectrum is flat in the rigid frequency range. Most of the modelling error is due to uncertainty in the mathematical representation with a small portion resulting in random variability of materials, mechanical joints, etc. The modelling error response distribution can be summarized as:

$F_{ME} = 1.0$

$\beta_{C_{ME}} = 0.15$

$\beta_{R_{ME}} = 0.05$

$\beta_{U_{ME}} = 0.14$

5.1.3.3 Damping

Since the components are rigid, there is no variability in response due to variability in damping, and the analysis is neither conservative or unconservative, i.e.,

$F_D = 1.0$

$\beta_{C_D} = 0.0$

5.1.3.4 Combination of Modes

There is likewise no conservatism or unconservatism due to combination of modes since the response is a single mode rigid body response. Therefore

$F_{MC} = 1.0$

$\beta_{R_{MC}} = \beta_{U_{MC}} = 0.0$

5.1.3.5 Combination of Earthquake Components

Individual geometries and failure modes had to be considered in developing response factors and their variability for combination of earthquake components. The design specifications for all components required that the worst horizontal direction response be combined with the vertical response by absolute summation. Reference 58 suggests that combination of response for all three directions of earthquake by the square-root-of-the-sum-of-the-squares method is median centered.

Alternatively, it is recommended (Reference 65) that directional effects be combined by taking 100% of the effects due to motion in one direction and 40% of the effects from the two remaining principal directions of motion as a median centered estimate.

The effect of SRSS combination of three components compared to the direct addition of two depends on the relative magnitudes of the two horizontal load components together with the vertical components and the geometry of the structures. For instance, if the two horizontal load components are approximately equal, and the vertical component is small, the SRSS method results in an increase in stress of from approximately 40% for a square structure to 0% for a circular structure. Combining the effects by the 100%, 40%, 40% method for the same case results in the same 40% increase in stress as for the SRSS method and an increase of approximately 8% for a circular structure such as a vertical tank. If the two horizontal load components are approximately equal and result in stresses approximately equal to that from the vertical component, all stress combinations from either the SRSS or 100%, 40%, 40% method are less than the absolute sum of one horizontal plus vertical as was used in the original design of Zion components.

Depending on the geometry of the particular structure under consideration together with the relative magnitude of the individual load or stress components, the expected variation in stresses due to either the SRSS or the 100%, 40%, 40% method of load combinations is from -30% to +40% when compared with the original design method.

On the basis that Lawrence Livermore Laboratory will provide fragility parameters (responses) that are median centered, whether by the SRSS method, 100%, 40%, 40% method or some other criterian developed in the SSMRP, the response factor for combination of earthquake components will, in the general case, be unity. Considering the -30% to +40% range to be approximately a ± 2 logarithmic standard deviation range, the variability on response, for the gerneral case, is 0.17. This is considered to be partially random due to randomness in earthquake phasing and part uncertainty due to the generic treatment of all geometries and relative magnitudes of response to the three component of earthquake. The estimated distributions are:

$$\beta_{R_{ECC}} = 0.1$$

$$\beta_{U_{ECC}} = 0.14$$

5.1.3.6 Combined Response Factor and Variabilities for Rigid Components Qualified by Static Analysis

The combined response factor and variabilities for the general case of rigid components qualified by static analyses, are:

$$F_R = 1.0$$

$$\beta_C = 0.23$$

$$\beta_R = 0.12$$

$$\beta_U = 0.20$$

5.2 RESPONSE FACTORS FOR FRAGILITY DESCRIPTIONS DERIVED FROM TEST DATA

In Chapter 4, fragility descriptions were developed for generic classes of equipment utilizing military shock test data. Also, the reactor protection system and diesel generator control system fragility descriptions were derived from qualification test reports.

Reference 58 discusses the sources and magnitudes of variability in test response. Several parameters are addressed which contribute to test response variability. They are:

Damping
Boundary Conditions
Spectral Shape
Instrumentation and Control Error
Acceleration Time History Variation
Variability Due to Use of Spectral Methods
Multidirectional Coupling Effects

The variables cited as being sources of variability in responses determined by analysis do not correspond directly to the parameters cited for testing; thus, a cross relationship needs to be established. Damping is, of course, a direct correspondence. Spectral shape, I&C error and variability due to spectral methods are all part of the qualifications methods category. Acceleration time history variation is applicable to the synthesized multiple sine beat testing used in the SAFEGUARD shock test program (References 13, 61 and 62). Multidirectional coupling effects is a category analogous to combination of earthquake components.

The response variabilities for the generic classes of equipment whose fragility descriptions were developed from military shock test data, and for plant specific components whose fragility descriptions were developed from qualification test data, are different and are developed separately. In addition, two different methods were used to derive fragility descriptions from the SAFEGUARD program shock test data and each method will be treated independently.

5.2.1 Response Factors for ZION Specific Components

Fragility descriptions for the diesel generator engine and generator control panels, the reactor protection system electronic cabinets and the static inverter were developed from qualification test data. The qualification tests were uniaxial sine beat tests that imposed a single frequency at a time.

5.2.1.1 Qualification Method

Sine beat testing was conducted for a broad frequency range, resulting in a flat envelope spectra; hence, the spectral shape factor is not applicable. I&C error as discussed in Reference 58, is applicable to spectral testing methods as are currently applied but is not applicable to single frequency sine beat tests. The test method itself, i.e., sine beat testing is considered to be median centered for only those components that respond in a single degree of freedom or in widely separated modes. An approximate lower bound factor for unconservatism for equipment that responds in a multimode manner is about 0.67. Considering this to be a minus two logarithmic standard deviation value with unity as a plus two logarithmic standard deviation value, the median response factor and its logarithmic standard deviation are:

$$F_{R_{QM}} = 0.82$$

$$\beta_{QM} = 0.10$$

The variability is considered to be mostly uncertainty in the response characteristics of the equipment such that

$$\beta_{R_{QM}} = 0.05$$

$$\beta_{U_{QM}} = 0.09$$

5.2.1.2 Boundary Conditions

Boundary conditions are addressed in Reference 58. The response factor is considered to be 1.0 as there is no deliberate bias. For large floor mounted cabinets with unspecified bolt torque, Reference 58 suggests that the variabilities in response, defined as logarithmic standard deviations, are:

$$\beta_{R_{BC}} = 0.05$$

$$\beta_{U_{BC}} = 0.05$$

5.2.1.3 Damping

Response factors and variabilities for damping are as specified for analysis. Since the fragility parameter (in these cases, spectral acceleration at the equipment/structure interface) will include median centered damping, the response factor for damping is unity. The variability on response due to damping variability varies with the applicable spectrum and the equipment fundamental frequency. An average value to cover the frequency range of electrical and control equipment is about 0.15. The variability is considerd to be about equal for random and modelling uncertainty with modelling uncertainty being slightly more predominant. The estimated values are

$$\beta_{R_D} = 0.10$$

$$\beta_{U_D} = 0.11$$

5.2.1.4 Earthquake Component Combination

Fragility descriptions were based upon single axis tests and any effects of multiaxial coupling are not included. In one limit, the critical component could have been oriented such that the fragility level measured could be as much as a factor of $\sqrt{3}$ nonconservative. In the other extreme, the critical component malfunction would have coencided exactly along one of the major axes of the test input. Applying the properties of the lognormal distribution, the median response factor is computed to be about 0.76. In other words, the fragility description derived from uniaxial tests is considered to be unconservative to the extent that the median fragility is about 76% of the derived fragility. The variability is estimated to be about 0.1.

The unconservatism in the derivation of the fragility description is, however, offset by the conservatism inherent in assuming that the median centered response vector, to be input into SEISIM, will be aligned with the weak axis of the component. Lawrence Livermove Laboratories, in generating response at the equipment/structure interface, will combine the three orthogonal responses in a median centered combination and the result will be a scalar value of spectral acceleration. Assuming that the eqrthquake component response combination will be similar to the 100%, 40%, 40% median centered recommendation from Reference 65, the minimum response along the component critical axis could be 40% of the scalar value input into SEISIM. The maximum response, for direct alignment of the median centered earthquake acceleration vector along the weak axis of the component, would be 100% of the scalar value input into SEISIM. In this case the response loading is conservatively specified. Applying the properties of the lognormal distribution, the response factor is 1.58. The estimated logarithmic standard deviation on this factor is 0.15. The two response factors associated with combination of earthquake components are combined as a product and the resulting response factor is 1.20. This means that the median component fragility, when compared to a median randomly oriented response vector, is understated by a factor of 1.2. The logarithmic standard deviations can be combined by the SRSS method to yield 0.18. The random portion is associated with the random orientation of the earthquake response vector with respect to the equipment axis; thus, β_R = 0.15. The orientation of the weak axis test direction is considered to be all uncertainty. Summarizing, for earthquake component combination, applicable to fragility descriptions derived from single axis tests, the response factor and its variabilities are:

$$F_{R_{ECC}} = 1.2$$

$$\beta_{C_{ECC}} = 0.18$$

$$\beta_{R_{ECC}} = 0.15$$

$$\beta_{U_{ECC}} = 0.10$$

The combined response factor and variabilities for plant specific components, whose fragility descriptions are based on qualification tests, are:

$F_R = 0.98$

$\beta_C = .26$

$\beta_R = .19$

$\beta_U = .18$

5.2.2 RESPONSE FACTORS AND VARIABILITIES FOR FRAGILITY DESCRIPTIONS DERIVED FROM SHOCK TEST DATA USING THE CORPS OF ENGINEERS METHODOLOGY (METHOD A)

The shock tests conducted for the SAFEGUARD program were, for the most part, single axis tests with complex waveforms consisting of superimposed sine beats. A control accelerometer was monitored to ensure that the test response spectrum was within specified tolerances. The specified tolerances were minus 10% and plus 20%. Limited biaxial testing was conducted with the same type of waveform input. Fragility descriptions developed in Sections 4.3.7.2 are based on the uniaxial tests. Biaxial data were included but were scaled to an equivalent uniaxial input for consistency.

Many of the variables inherent for equipment whose fragility descriptions were developed from sine beat qualification tests are applicable to Method A. There are some differences, however, and they will be quantified in this section.

5.2.2.1 Qualification Method

Spectral shape, I & C Error and variability due to the use of spectral methods were stated to be included in qualification methods. First, the tolerance on the test response spectrum is considered. Fragility descriptions developed in Chapter 4 are based upon the required response spectrum. The test response spectra had tolerances of +20% and -10%. The resulting median factor of conservatism in the tests was 1.04. The approximate logarithmic standard deviation in the test response spectrum was about 0.11. This is based on the assumption that the specified tolerances were maintained 90% of the time. A review of some of the control accelerometer data supports this assumption. The random and uncertainty portions are considered to be approximately equal with:

$$\beta_{R_{SS}} = 0.08$$
$$\beta_{U_{SS}} = 0.08$$

I & C error, as discussed in Reference 58, is not applicable to the form of testing used in the SAFEGUARD program. The time history inputs were generated analytically for superimposed multiple sine beats as opposed to using a spectral analyzer to generate a time history input. Variability due to the use of spectral methods, as discussed in Reference 58, is applicable. The use of spectral methods for testing is considered to be median centered with a resulting response factor of unity. The variability, as discussed in Reference 58, is:

$$\beta_{SM} = 0.11$$

$$\beta_{R_{SM}} = 0.05$$

$$\beta_{U_{SM}} = 0.10$$

Combining the response factors and variabilities due to qualification method results in:

$$F_{R_{QM}} = 1.04$$

$$\beta_{C_{QM}} = 0.16$$

$$\beta_{R_{QM}} = 0.09$$

$$\beta_{U_{QM}} = 0.13$$

5.2.2.2 Boundary Conditions

The effect of boundary conditions is included in the U.S. Corps of Engineers methodology used to develop fragility description and is not applicable to the response factors for Method A.

5.2.2.3 Damping

There are two considerations to account for variability in response due to damping. If median damping is specified for the fragility parameter (in this case, spectral acceleration at 5% damping) the response factor for damping is unity. The variability was defined in the previous section to be about 0.15 with β_R = 0.10 and β_U = 0.11. There is an additional variability that must be considered. The SAFEGUARD shock test inputs were defined in terms of undamped spectra. A typical synthesized sine beat input was run through a response spectrum generation program to obtain typical damped spectra for comparison to undamped spectra. It was determined that a scale factor of 2/3 could be applied to the undamped required response spectra to obtain 5% damped spectra, 5% being considered a median value of damping for electrical and control equipment. There is variability in this scale factor over the frequency range of interest which was determined to be approximately 0.13. The variability is considered to be predominantly uncertainty due to the fact that it covers a broad frequency range and range of sine beat inputs. The estimated distribution between randomness and uncertainty is

$$\beta_R = .08$$

$$\beta_U = .10$$

Combining the factors and variabilities for damping results in:

$$F_{R_D} = 1.0$$

$$\beta_{C_D} = 0.20$$

$$\beta_{R_D} = 0.13$$

$$\beta_{U_D} = 0.15$$

5.2.2.4 Acceleration Time Histories

There can be a large variability in component response due to the acceleration time histories selected to result in a given spectrum. Reference 58 discusses this variability and provides an estimate that the combined logarithmic standard deviation is about 0.17 with

$$\beta_{R_{TH}} = 0.14$$

$$\beta_{U_{TH}} = 0.10$$

The superimposed multiple sine beat input used in testing SAFEGUARD equipment is assumed to be median centered such that the response factor is unity.

5.2.2.5 Combination of Earthquake Components

Multidirectional coupling effects for testing was discussed in the previous section. Considering that the fragility description is based upon uniaxial tests and the response input to SEISIM will be a scalar quantity, assumed to coincide with the weak axis of the component, the response factor and its variability are estimated to be:

$$F_{R_{ECC}} = 1.2$$

$$\beta_{C_{ECC}} = 0.18$$

$$\beta_{R_{ECC}} = 0.15$$

$$\beta_{U_{ECC}} = 0.10$$

The combined effects of the variables applicable to fragility descriptions developed from SAFEGUARD test data by Method A are:

$F_R = 1.25$

$\beta_C = 0.35$

$\beta_R = 0.26$

$\beta_U = 0.24$

5.2.3 RESPONSE FACTORS AND VARIABILITY FOR FRAGILITY DESCRIPTIONS DERIVED FROM SHOCK TEST DATA USING METHOD B

All response factors and variabilities defined for Method A are applicable to Method B. In addition, bondary conditions must be considered. The Corps of Engineers methodology, Method A, included variability for boundary conditions in the fragility description. Method B, which is just the statistical processing of observed malfunctions, does not address any difference in responses due to differences in boundary conditions in the test lab vs boundary conditions in a plant installation. Reference 58 discusses this variability and provides estimates for different mounting conditions. The equipment under consideration is predominantly floor mounted, bolted in the laboratory and welded in the ZION installations. The estimated variabilities in response, expressed as logarithmic standard deviations are:

$\beta_{C_{BC}} = 0.11$

$\beta_{R_{BC}} = 0.05$

$\beta_{U_{BC}} = 0.10$

The response factor due to boundary conditions is considered to be unity.

Combining the boundary conditions variabilities with variabilities from other sources applicable to Method B results in:

$F_R = 1.25$

$\beta_C = 0.37$

$\beta_R = 0.26$

$\beta_U = 0.26$

5.3 GENERIC RESPONSE FACTORS AND VARIABILITY FOR COMPONENTS TO BE REANALYZED

During the SSMRP, Lawrence Livermore Laboratory will conduct multiple time history analyses of the NSSS system including the RPV, Steam Generators, Pumps, Pressurizer and interconnecting piping. They will also conduct multiple time history analyses of selected engineered safety systems piping. During these analyses some of the sources of response variability will be explored by conducting sensitivity and parametric studies. Other parameters that influence subsystem response will, however, be fixed, and estimates of response variabilities due to the use of deterministic methods should be factored into the overall response distribution function that is ultimately input into the risk model.

In Section 5.1 parameters that affect subsystem response were identified as:

Qualification Method
Modelling Error
Damping
Modal Response Combination
Earthquake Component Response Combination

It is understood that in the LLL subsystem response analysis program, the mode superposition time history analysis method will be used to conduct multiple time history analyses, which represent the range of variability in seismic input. LLL will also vary damping to cover the range of response due to variations in damping. The model geometries, boundary conditions and material properties will remain constant. Earthquake component responses will be combined by a median centered method to be determined. Dispersion of response due to some of the parameters listed above will be covered by the LLL study while dispersion of response for parameters treated deterministically in the LLL study will be provided in this study. Each of the above parameters, that contribute to variability in subsystem response, are examined.

5.3.1 QUALIFICATION METHOD

Time history mode superposition analysis is considered to be median centered. The variability in results is due primarily to the input time histories, modelling errors and damping used in the analyses. LLL will cover a broad range of time history input which will provide a response distribution based upon variation in earthquke time histories. The mathematical solution method is considered to be sufficiently accurate and repeatable that no additional variability needs to be assigned for qualification method.

5.3.2 MODELLING ERROR

Bias and variation in response due to modelling error results from two sources:

a) Mode Shape
b) Frequency

Model element stiffnesses are influenced by the geometric input, material properties and assumptions regarding the behavior of integral and non-integral joints. System stiffness is influenced by individual element stiffnesses and the mathematical treatment of boundary conditions in the model. Model element masses are influenced by the density of material, geometric description of the material and description of lumped masses, such as the case of valves in a piping system. Mode shape and frequency variabilities result directly from the mathematical representation of stiffness and mass. The variability in response is directly proportional to the variability in mode shape, but the variability in response due to frequency shift is a function of the time history input and the system frequencies.

Based upon individual experience in performing dynamic analyses, the mode shape variability and resulting subsystem response variability due to mode shape, when expressed as a logarithmic standard deviation, , is about 0.15 for multidegree-of-freedom systems such as complex piping systems. The variation in response due to frequency can best be described by comparing to a response spectrum approach of analysis. Consider a response spectrum that corresponds to a particular time history input. If the spectrum is flat at the frequency or frequencies of interest, there is no variability in response due to frequency shift. If, however, the spectral acceleration is changing rapidly at the frequency of interest, the response becomes very sensitive to frequency.

Examination of the original ZION design spectra for the Class 1 structures reveals that there is considerable change in spectral acceleration in the range of piping system fundamental frequencies. At the lower building elevations, the spectral acceleration change is not as pronounced as at high elevations. The reactor building spectra are also significantly different than the auxiiary building spectra. It would be desirable to have response variability defined for each floor level of each critical structure that houses piping systems and equipment that are being reanalyzed. This can be approximated for the original design spectra and the results can be applied to the new analyses under the assumption that the original design spectra were representative of response that will be obtained in the SSMRP.

Figure 5-1 is a typical design spectrum for the Turbine-Auxiliary building at elevation 642 feet. Five percent damping was previously stated to be a best estimate of median damping, therefore, all reference will be made to the 5 percent damped response spectrum.

For a component or system that responds predominantly in one mode, the change in response can be defined in probabilistic terms for a change in frequency given in probabilistic terms. This was done for all elevations of the Turbine-Auxiliary-Diesel Generator building, reactor building and crib house, for which design spectra were originally derived.

Reference 58 suggests that the logarithmic standard deviation on frequency, β_F, is about 0.3. The actual frequency change depends upon the frequency of interest, and the associated change in response depends upon the frequency of interest and the shape of the response spectrum. A sample problem is shown in Reference 58 to illustrate the process of quantifying response variability due to frequency variability. For this study, representative frequencies, representative rates of change of spectral acceleration with frequency and associated logarithmic standard deviations for these changes are sought. The following procedure was used to generate this information.

First, the assumption was made that the fundamental piping frequencies are within the amplified region of the design respose spectrum. This is typical of piping systems. For ZION, the Architect Engineer provided piping design guides for piping 8 inches in diameter and smaller to position supports such that piping would not be in resonance with the building structure. The guidelines provided support spacing to keep the fundamental piping frequencies away from the peak of the design spectrum. For piping greater than 8 inches in diameter, a dynamic analysis was conducted, and it is unclear where the fundamental frequency would lie in comparison to the building frequency. Typical frequencies on either side of the peak of the response spectrum need to be examined. Figure 5-1 shows frequencies F_1 and F_2, which are frequencies half-way between the frequency at the peak of the response spectrum and the frequencies on either side of the peak where the spectral acceleration corresponds to the zero period acceleration (ZPA). The frequencies on either side of the peak, corresponding to the zero period acceleration value are denoted in Figure 5-1 as F_L and F_Z, respectively.

After establishing representative frequencies F_1 amd F_2. the frequency shift, ΔF_1, and ΔF_2, can be computed using equation 2-7 and the logarithmic standard deviation value of 0.3 on frequency. With the frequencies F_1 and F_2 and logarithmic standard deviation frequency shifts, ΔF_1 and ΔF_2, the changes in spectral accelerations, ΔSa_1 and ΔSa_2 can be determined from the response spectrum. Then, using a form of equation 2-7, the logarithmic standard deviation on response due to frequency shift, from frequencies F_1 and F_2, can be computed. Table 5-2 tabulates the elevations in each of the three buildings, the logarithmic standard deviation on response due to frequency shift, β_{F_1} and β_{F_2} and the average of β_{F_1} and β_{F_2}, $\overline{\beta}_F$. For almost all floor levels of the three buildings there is not a great deal of difference between β_{F_1} and β_{F_2} such that $\overline{\beta}_F$ is considered to be representative throughout the frequency range of interest for piping systems.

Recalling that, for lognormal distributions, the logarithmic standard deviations can be combined by the square-root-of-the-sum-of-the-squares-method, the response variability due to modelling error becomes:

$$\beta_{ME} = \sqrt{\beta_{MS}^2 + \beta_F^2}$$

Table 5-2 portrays the combination for each floor level using a value for β_{MS} equal to 0.15 as previously described. Since there is no intended bias in the modelling of the SSMRP subsystem, the response factor for modelling error is considered to be unity.

The variabilities in response due to modelling error result primarily from modelling uncertainty. There is some random variability due to variation in material properties, random variability in geometric tolerances and in structural characteristics of mechanical joints and supports. Table 5-2 approximates the distribution between random and modelling uncertainty variability.

5.3.3 DAMPING

Damping will be varied in the SSMRP study, and no additional dispersion needs to be added to the computed responses. The variation in response due to variation in damping is a strong function of frequency. Figure 5-1 displays 2 percent and 5 percent damped response spectra and the variation in response between the two spectra as a function of frequency is clearly evident.

5.3.4 MODAL RESPONSE COMBINATION

This applies only to responses computed by the response spectrum method. LLL will be using the mode superposition time history method and as such this parameter is not applicable.

5.3.5 COMBINATION OF EARTHQUAKE COMPONENTS

LLL plans to combine responses to the three directions of earthquakes by a median centered method to be determined. Since the method will be median centered, the response factor would be 1.0. Reference 58 suggests that studies have shown the logarithmic standard deviation on response, due to combination of earthquake components, to be on the order of 0.15. This variability on response is purely a random process due to random phasing of earthquake components, thus:

$$\beta_{R_{ECC}} = 0.15$$

$$\beta_{U_{ECC}} = 0.0$$

Table 5-3 summarizes the variabilities that should be applied to new subsystem analyses conducted by LLL. The variabilities are expressed as logarithmic standard deviations on response.

TABLE 5-1 RESPONSE FACTORS

GENERIC CATETORY	SPECIFIC COMPONENT	LOCATION		QUALI-FICATION METHODS	FRAGILITY PARAMETER	RESPONSE FACTOR	LOGARITHMIC STD. DEVIATION			NOTES
		BLDG.	ELEV.				COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	
Reactor Coolant System, Class 1 Vessels & Supports	Reactor Pressure Vessel	Containment	584	Response Spectrum	Moment	1.0	0.32	0.18	0.26	
Reactor Coolant System, Class 1 Vessels & Supports	Steam Generator	Containment	590	Response Spectrum	Spectral Acceleration	1.0	0.28	0.20	0.20	
Reactor Coolant System, Class 1 Vessels & Supports	Pressurizer	Containment	590	Static Coefficient	Spectral Acceleration	1.0	0.25	0.15	0.20	
Reactor Coolant System, Class 1 Vessels & Supports	Reactor Intervals	Containment	584	Response Spectrum	Spectral Acceleration	1.0	0.28	0.19	0.20	
Control Rods & Drives	Control Rod Housing	Containment	600	Response Spectrum	Spectral Acceleration	1.0	0.23	0.18	0.15	
Main Coolant Pumps	Reactor Coolant Pump	Containment	591	Response Spectrum	Spectral Acceleration	1.0	0.28	0.20	0.20	
NSSS Piping	Generic	Containment	584'	Response Spectrum	Moment	1.0	0.32	0.18	0.26	
Large Diameter Piping, 8" & Greater	Generic	All	All	Response Spectrum	Moment	See	Table 5-3			
Intermediate Diameter Piping, 2½"-8"	Generic	All	All	Static Coefficient	Moment	See	Table 5-3			
Large Vertical Vessels & Heat Exchangers with Formed Heads	Generic	All	All	Static Analysis	Spectral Acceleration	1.0	0.31	0.20	0.24	

TABLE 5-1 RESPONSE FACTORS
(Continued)

GENERIC CATETORY	SPECIFIC COMPONENT	LOCATION		QUALI-FICATION METHODS	FRAGILITY PARAMETER	RESPONSE FACTOR	LOGARITHMIC STD. DEVIATION			NOTES
		BLDG.	ELEV.				COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	
Large Vertical Vessels & Heat Exchangers with Formed Heads	Accumulator Tanks	Containment	560	Static Analysis	Spectral Acceleration	1.0	0.17	0.14	0.1	
Large Vertical Vessels & Heat Exchangers with Formed Heads	RHR Heat Exchanger	Auxiliary	560	Response Spectrum	Spectral Acceleration	1.0	0.46	0.25	0.39	
Large Flat Bottom Storage Tanks	Condensate Storage Tank	Outdoors	Grade	Response Spectrum	Peak Ground Acceleration	0.92	0.28	0.20	0.19	
Large Flat Bottom Storage Tanks	Diesel Oil Storage Tank	Auxiliary	560	Static Analysis	Zero Period Acceleration	1.0	0.23	0.17	0.16	
Large Horizontal Vessels & Heat Exchangers	Component Cooling Water Heat Exchanger	Auxiliary	560	Response Spectrum	Spectral Acceleration	1.37	0.50	0.27	0.42	
Large Horizontal Vessels & Heat Exchangers	Generic	All	All	Static Analysis	Spectral Acceleration	1.37	0.31	0.20	0.24	
Small-Medium Vessels & Heat Exchangers	Boron Injection Tank	Auxiliary	601	Response Spectrum	Spectral Acceleration	1.0	0.36	0.21	0.29	
Small-Medium Vessels & Heat Exchangers	Generic	All	All	Static Analysis	Zero Period Acceleration	1.2	0.21	0.15	0.14	
Buried Pipe	Service Water from Crib House	NA	Below Grade	Static Analysis	Peak Ground Acceleration	1.0	0.43	0.1	0.42	
Buried Pipe	Auxiliary Feed Water from Condensate Storage Tank	NA	Below Grade	Static Analysis	Peak Ground Acceleration	1.0	0.43	0.1	0.42	

TABLE 5-1 RESPONSE FACTORS
(Continued)

GENERIC CATETORY	SPECIFIC COMPONENT	LOCATION		QUALI-FICATION METHODS	FRAGILITY PARAMETER	RESPONSE FACTOR	LOGARITHMIC STD. DEVIATION			NOTES
		BLDG.	ELEV.				COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	
Large Vertical Centrifugal Pumps with Motor Drive	Service Water Pumps	Crib House	594	Response Spectrum	Spectral Acceleration	0.94	0.27	0.17	0.21	
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compressors	Residual Heat Removal Pump	Auxiliary	542	Response Spectrum	Spectral Acceleration	1.0	0.32	0.20	0.25	
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compressors	Safety Injection Pump	Auxiliary	560	Static Analysis	Spectral Acceleration	1.37	0.22	0.15	0.16	
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compressors	Centrifugal Charging Pump	Auxiliary	579	Static Analysis	Spectral Acceleration	1.37	0.22	0.15	0.16	
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compressors	Generic Pumps & Compressors	All	All	Static Analysis	Spectral Acceleration	1.25	0.35	0.26	0.24	
Large Motor Operated Valves	Generic	All	All	Static Analysis	Peak Piping Acceleration	1.2	0.24	0.16	0.18	(1)
Large Hydraulic & Air Operated Valves	Main Steam Isolation Valve	Auxiliary	580	Static Analysis	Zero Period Acceleration	1.0	0.18	0.11	0.14	
Large Hydraulic & Air Operated Valves	Generic	All	All	Static Analysis	Peak Piping Acceleration	1.25	0.35	0.26	0.24	(1)
Large Check, Spring Relief & Manual Valves	Generic	All	All	Static Analysis	Peak Piping Acceleration	1.25	0.35	0.26	0.24	(1)

TABLE 5-1 RESPONSE FACTORS
(Continued)

GENERIC CATETORY	SPECIFIC COMPONENT	LOCATION		QUALI-FICATION METHODS	FRAGILITY PARAMETER	RESPONSE FACTOR	LOGARITHMIC STD. DEVIATION			NOTES
		BLDG.	ELEV.				COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	
Small Motor Operated Valves	Generic	All	All	Static Analysis	Peak Piping Acceleration	1.2	0.24	0.16	0.18	(1)
Small Miscellaneous Valves ≲8"	Generic	All	All	Static Analysis	Peak Piping Acceleration	1.25	0.35	0.26	0.24	(1)
Emergency A.C. Power Units	Generator Control Panel	Auxiliary	592	Test	Spectral Acceleration	0.98	0.26	0.19	0.18	
Emergency A.C. Power Units	Engine Control Panel	Auxiliary	592	Test	Spectral Acceleration	0.98	0.26	0.19	0.18	
Emergency A.C. Power Units	Engine & Generator Components	Auxiliary	592	Static Analysis	Zero Period Acceleration	1.37	0.22	0.15	0.16	
Emergency D.C. Power Units	Battery Racks	Auxiliary	642	Response Spectrum	Spectral Acceleration	1.37	0.38	0.23	0.31	
Emergency D.C. Power Units	Batteries	Auxiliary	642	Test	Spectral Acceleration	1.25	0.35	0.26	0.24	
Switchgear	Generic	Auxiliary	617	Test	Spectral Acceleration	1.25	0.37	0.26	0.26	
Transformers	Generic	Auxiliary	617	Static Analysis	Spectral Acceleration	1.25	0.35	0.26	0.24	
Local Instruments & Transmitters	Generic	All	All	Test	Spectral Acceleration	1.25	0.35	0.26	0.24	
Instrument Panels & Racks	Generic	Auxiliary	642	Test	Spectral Acceleration	1.25	0.37	0.26	0.26	
Control Panels & Racks	Reactor Protection System	Auxiliary	642	Test	Spectral Acceleration	0.98	0.26	0.19	0.18	
Control Panels & Racks	Generic	Auxiliary	642	Test	Spectral Acceleration	1.25	0.37	0.26	0.26	

TABLE 5-1 RESPONSE FACTORS
(Continued)

GENERIC CATETORY	SPECIFIC COMPONENT	LOCATION		QUALI-FICATION METHODS	FRAGILITY PARAMETER	RESPONSE FACTOR	LOGARITHMIC STD. DEVIATION			NOTES
		BLDG.	ELEV.				COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	
Relay Cabinets	Generic	Auxiliary	642	Test	Spectral Acceleration	1.25	0.37	0.26	0.26	
Motor Control Centers	Generic	Auxiliary	617	Test	Spectral Acceleration	1.25	0.37	0.26	0.26	
Breaker Panels	Generic	Auxiliary	617-642	Test	Spectral Acceleration	1.25	0.37	0.26	0.26	
Static Inverters	Zion Specific Inverter	Auxiliary	642	Test	Spectral Acceleration	0.98	0.26	0.19	0.18	
Air Conditioning & Air Handling	Containment Fan Coolers	Containment	590	Response Spectrum	Spectral Acceleration	1.37	0.34	0.23	0.25	
Air Conditioning & Air Handling	Generic	All	All	Static Analysis	Spectral Acceleration	1.25	0.35	0.26	0.24	
Ducting	Generic	All	All	Static Analysis	Zero Period Acceleration	1.04	0.38	0.23	0.3	
Cable Trays	Generic	All	All	Static Analysis	Zero Period Acceleration	0.94	.15	.15	0.0	
Offsite Power	Generic	NA	Ground	None	Peak Ground Acceleration	1.0	.15	.15	0.0	

Note: (1) Response factors for valves should be combined with response factors for piping that is reanalyzed by LLL. See Table 5-3.

TABLE 5-2

VARIABILITY IN RESPONSE DUE TO MODELLING ERROR

BUILDING	ELEVATION	β_{f1}	β_{f2}	β_{f}	$\beta_{C_{ME}}$	$\beta_{R_{ME}}$	$\beta_{U_{ME}}$
Turbine-Aux	642'	.24	.24	.24	.28	.10	.26
Turbine-Aux	630'	.20	.26	.23	.27	.10	.25
Turbine-Aux	617'	.21	.28	.24	.28	.10	.26
Turbine-Aux	592'	.20	.20	.20	.25	.10	.23
Turbine-Aux	580'	.20	.20	.20	.25	.10	.23
Turbine-Aux	560'	.13	.11	.12	.19	.05	.18
Turbine-Aux	542'	.13	.11	.12	.19	.05	.18
Reactor	617'	.14	.18	.16	.22	.10	.20
Reactor	590'	.23	.13	.18	.23	.10	.21
Reactor	581'10"*	.25	.24	.24	.28	.10	.26
Reactor	568'	.12	.11	.11	.19	.05	.18
Crib House	594'	.24	.32	.28	.32	.15	.28
Crib House	552'	.21	.23	.22	.27	.10	.25

*Shield Wall

TABLE 5-3

SUMMARY OF SUBSYSTEM RESPONSE VARIABILITY FOR SUBSYSTEMS TO BE REANALYZED BY LLL

BUILDING	ELEVATION FT.	VARIABILITY DUE TO FREQUENCY β_f	VARIABILITY DUE TO MODE SHAPE β_{MS}	VARIABILITY DUE TO EARTHQUAKE COMPONENT β_{ECC}	COMPOSITE VARIABILITY	RANDOM VARIABILITY	MODELLING UNCERTAINTY VARIABILITY
Turbine-Aux	642'	.24	.15	.15	.32	.18	.26
Turbine-Aux	630'	.23	.15	.15	.31	.18	.25
Turbine-Aux	617'	.24	.15	.15	.32	.18	.26
Turbine-Aux	592'	.20	.15	.15	.29	.18	.23
Turbine-Aux	580'	.20	.15	.15	.29	.18	.23
Turbine-Aux	560'	.12	.15	.15	.24	.16	.18
Turbine-Aux	542'	.12	.15	.15	.24	.16	.18
Reactor	617'	.16	.15	.15	.27	.18	.20
Reactor	590'	.18	.15	.15	.28	.18	.21
Reactor	581'10"*	.24	.15	.15	.32	.18	.26
Reactor	568'	.11	.15	.15	.24	.16	.18
Crib House	594'	.28	.15	.15	.35	.21	.28
Crib House	552'	.22	.15	.15	.31	.18	.25

*Shield Wall

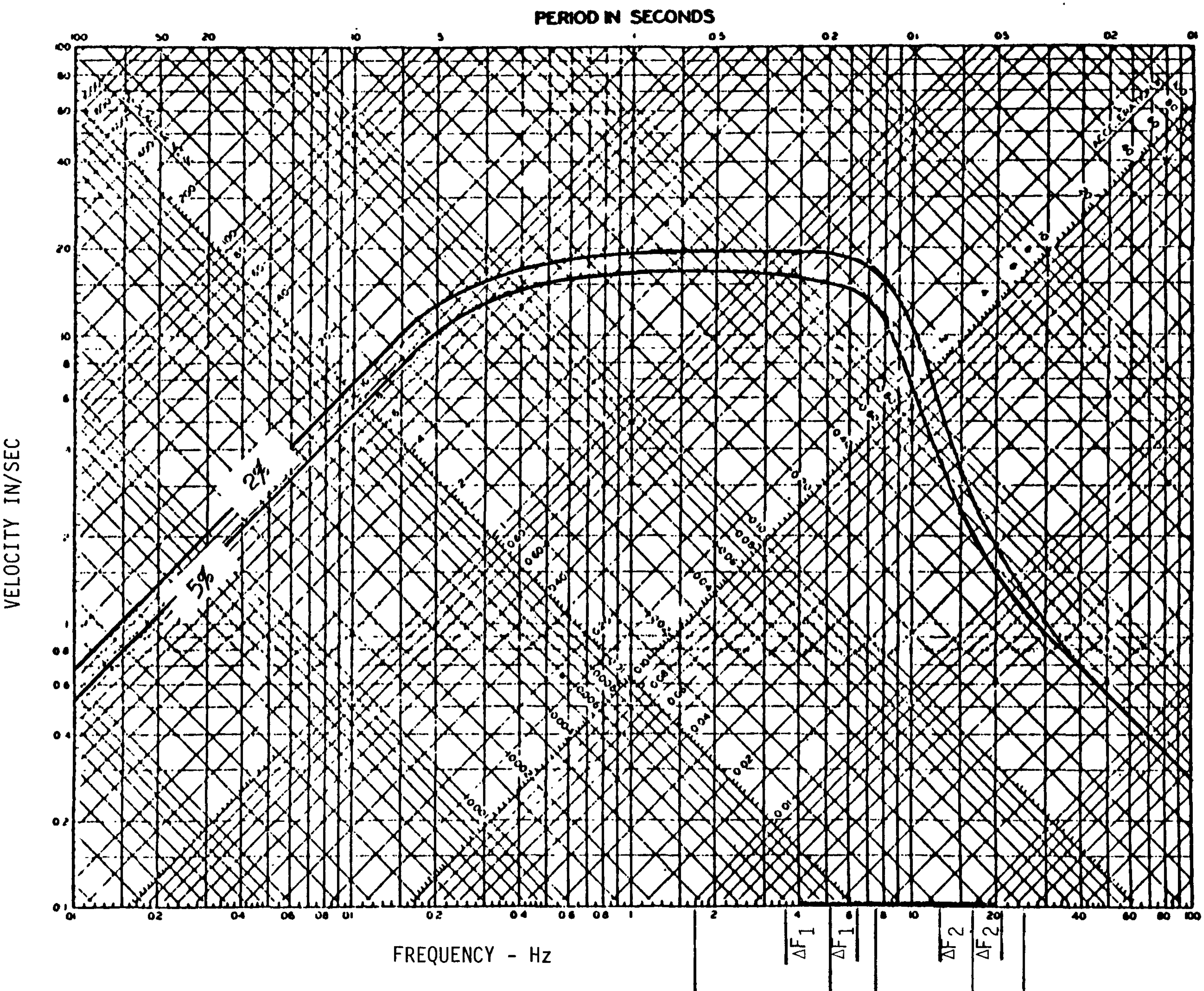


FIGURE 5-1
RESPONSE SPECTRA, DESIGN BASIS EARTHQUAKE
ELEVATION 642, AUXILIARY-TURBINE BUILDING

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64. Personal communication with Richard Bradshaw, U. S. Army Corps of Engineers, Huntsville Division.

65. Newmark, N. M. and W. J. Hall, "Development of Criteria for Seismic Review of Selected Nuclear Power Plants", report prepared for the U. S. Nuclear Regulatory Commission, 30 September 1977.

APPENDIX A

U.S. CORPS OF ENGINEERS HARDNESS

VERIFICATION METHODOLOGY AND PROCEDURES

SECTION 5

HARDNESS VERIFICATION METHODOLOGY AND PROCEDURES

5.0 HARDNESS VERIFICATION METHODOLOGY AND PROCEDURES

The overall reporting of hardness for the Safeguard facilities and TSE is provided in the Subsystem Hardness Assurance Report (SHAR), Reference 3. A major input to the SHAR is the set of hardness numbers originating from verification activities within the TSE Shock Test Program and described in this document. These inputs from the TSE Shock Test Program are separately documented in the Subsystem Hardness Assurance Analysis (SHAA). This section provides the basic methodology applicable to both SHAA and SHAR followed by a detailed description of the SHAA methodology and procedures.

In both the SHAA and SHAR, the goal is to obtain a quantitative hardness number for every susceptible subsystem/environment combination exposed to the free field criteria described in Reference 4. To achieve this goal methodologies have been developed and are described herein.

Two hardness indices are defined that are compatible with the 97.7% survival probability. These are:

<u>Hardness Verification Index (H_V)</u> - A conservative ratio of failure threshold to local environment, which if one or greater, demonstrates hardness to a probability well above the requirement.

<u>Survival Probability (P_V)</u> - The probability that the subsystem or item will survive the free field criteria, Reference 4.

5.1 GENERAL SHAA/SHAR METHODOLOGY

Hardness verification in the Safeguard Program is characterized as a series of screening operations. Screening is defined as the process of eliminating TSE that are "safe" when a given engineering analysis can establish that fact. Items classified "safe" are dropped from further consideration. The quantitation of hardness in SHAA/SHAR is applied to all items that were not eliminated by the screening processes used to develop the susceptibility matrix, Figure 4-10 in Reference 1.

5.1 (Continued)

For the in-structure response environment, none of the TSE located inside structures was eliminated. The requirements for a quantitation of hardness in SHAA/SHAR are therefore established by the susceptibility matrix, Figure 4-10 in Reference 1.

> Each subsystem environment combination that has been established as susceptible shall be quantitatively rated by a SHAA/SHAR hardness index.

In the SHAA/SHAR methodology that follows one additional screening process is used. This additional screening is accomplished by two hardness numbers. The first is a conservative index and the second is more precise and requires an extension of the analysis used for the more conservative index. These indices were defined in paragraph 5.0 and are further developed in this section.

A quantitative hardness number can be obtained by determining the non-dimensional ratio of a failure threshold to an environment. If the threshold could be precisely determined and if the environment could be precisely determined then, the hardness ratio is:

$$H = \frac{T}{E}$$

where

H = hardness number

T = actual threshold in units

E = actual environment in same units as the threshold

Obviously T and E cannot be precisely determined and therefore H is not deterministic. In the SHAA/SHAR methodology, the hardness number is considered in a quasi-probabilistic sense. Accordingly a statistical statement is required for both T and E.

The statistical approach used in Safeguard SHAA/SHAR is to first comput a ratio of failure threshold to environment that fulfills the requirement with a margin adequate to permit a simplified computation. Let this computation be defined as:

$$H_V = \frac{\bar{T}-3\sigma_T}{\bar{E}+3\sigma_E}$$

5.1 (Continued)

where

H_V = hardness verification index

$\bar{T}-3\sigma_T$ = any threshold computation that has a value at least $3\sigma_T$ conservative on the low side and expressed in some units.

$\bar{E}+3\sigma_E$ = local environment that has a value at least $3\sigma_E$ conservative on the high side with the same units as the threshold.

In the specialized SHAA methodology both the failure threshold and local environment are normalized.

An H_V computation greater than one will provide a survival probability much greater than the Safeguard requirement of 97.7%. This was established using sample trial data. The margin in the hardness verification index (H_V) is adequate to account for errors in a non-precise computation.

Because of the large number of similar SHAA computations, a formalized procedure has been developed and is provided in paragraph 5.3. On the other hand, SHAR computations vary because of the numerous environment; and only a general approach is provided. See Reference 3. In both cases the environment value is taken directly from the Secondary Environmental Criteria evaluation. Prepublication results of the secondary environmental criteria study are in Reference 6.

If the computation results in a hardness verification index equal to or greater than one ($H_V \geq 1$), the item can be documented as hard, and no further consideration or analysis is required. Recording of the results is as follows:

H_V = (the computed value)

P_V >> 97.7%

Thus, the computation of H_V constitutes an additional screening process within the SHAA/SHAR methodology.

If a hardness verification index is less than one ($H_V < 1$), the hardness is demonstrated by a computation of P_V (survival probability). The computation of P_V is more involved than a computation of H_V, but a favorable P_V result will also meet the requirement although the item is "less hard" than an item which has a $H_V \geq 1$.

5.1 (Continued)

Methodologies for computing P_V is provided in paragraphs 5.1.1 and 5.1.2. Computations of the survival probability (P_V) requires as assumption that both the failure threshold and environment be normal distributions. Based on unpublished trial data the normal distribution assumption is reasonable. For environments other than in-structure response (SHAR), the evaluator must generate sufficient failure threshold data to approximate a normal distribution. For in-structure response (SHAA), a formal procedure has been developed to provide an adequate normal distribution for the threshold. This procedure is in paragraph 5.3. All the environments required for SHAA/SHAR have been evaluated and are presented in an approximate normal distribution form for the P_V computation. Therefore, when the simplified computation for H_V fails to provide the required hardness assurance ($H_V \geq 1$), the survival probability P_V is computed. If the survival probability P_V exceeds the 97.7% requirement, the item has been demonstrated hard and documented as follows:

$$H = 1$$

$$P_V = \text{(the computed value)}$$

which is to say that the actual numerical hardness is one or greater to a probability P_V.

It should be noted that the H_V computation is a screening process to eliminate some of the more detailed work required in computing the survival probability (P_V).

5.1.1 Derivation of Survival Probability (P_V)

Assume the existence of a probability density function for the threshold and for the environment. These probability density functions do not need to be normal distributions for the proof that follows.

The derivation of P_V is based on the logic diagram shown on Figure 5-1, Venn Diagram. On Figure 5-1, the failure threshold is plotted on the ordinate and the abscissa is the local environment. Both the ordinate and abscissa are in the same units and have the same scale. The two probability distributions are shown on the respective axes. For each distribution a lower limit and an upper limit are defined as T_I for the failure threshold and E_I for the environment. If the two distributions are plotted on the same axis and in the same units T_I and E_I are further defined as:

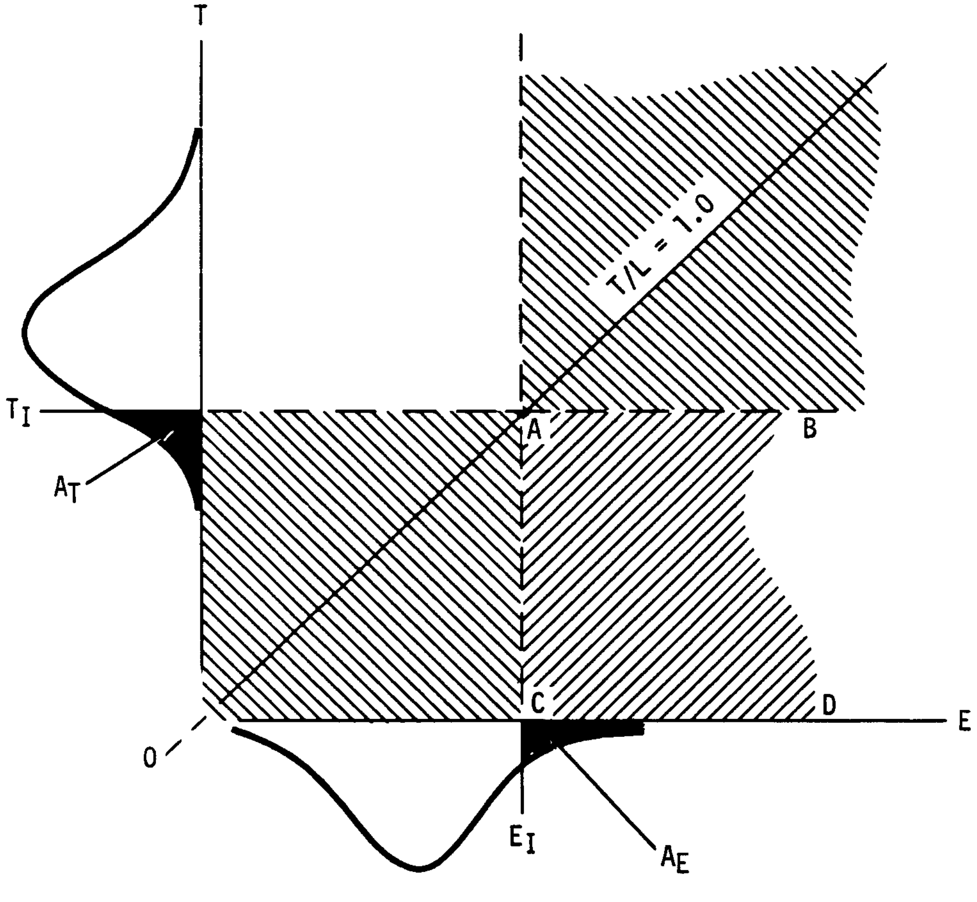

FIGURE 5-1 VENN DIAGRAM

5.1.1 (Continued)

$$T_I = E_I = X_I$$

where X_I, T_I, E_I are all points of the intercept.

A diagonal line, labeled T/L = 1 from the origin (Note: the origin is a limit) through the intercept of T_I and E_I is drawn. This line separates the failure region and the survival region. Four rectangles are identified on Figure 5-1, three are shaded. The shaded rectangles mean that all or part of the rectangle is in the failure region. Since the computation of probability can be performed only on complete rectangles, two probability numbers in the form of limits will be derived. One, the lower limit, is obtained from all three shaded rectangles and the upper limit is obtained from rectangle ABCD only.

From Figure 5-1, the statistical logic for all three shaded rectangles is:

$$(T/L < 1) \subset (E > E_I \cap T > T_I) \cup (E < E_I \cap T < T_I)$$

$$\cup (E > E_I \cap T < T_I)$$

where

T = random failure threshold

E = random local environment

P_V = probability $T/E \geq 1$

A_T = probability measure for failure threshold

A_E = probability measure for local environment

T_I = value of T at which the probability that the actual failure threshold will be less than A_T

E_I = value of E at which the probability that it will be exceeded is A_E

If T and E are statistically independent, the above logic equation translates to:

$$P(T/L < 1) < (1 - A_T) A_E + A_T (1 - A_E) + A_T A_E$$

5.1.1 (Continued)

Thus

$$P(T/L < 1), \text{ Failure upper bound} = A_T + A_E - A_T A_E$$

or

$$P(T/L > 1), \text{ Survival lower bound} = 1 - (A_T + A_E - A_T A_E)$$

In a similar manner, the logic expression for rectangle ABCD (only rectangle completely in the failure region) is written.

$$(T/L < 1) \supset (E > E_I \cap T < T_I)$$

translating

$$P(T/L < 1) > A_T A_E$$

$$P(T/L < 1), \text{ Failure lower bound } = A_T A_E$$

or

$$P(T/L > 1), \text{ Survival upper bound} = 1 - A_T A_E$$

and in summary

$$(1 - A_T A_E) > P_V > [1 - (A_T + A_E - A_E A_T)]$$

Because two of the rectangles on Figure 5-1, Ven Diagram, transcends the survival/failure line P_V can be any value between the limits given above.

In order to compute the P_V limits only, the areas A_T and A_E are required. Without extensive data and complete computer processing the results, these areas are virtually unobtainable. To circumvent this difficulty, normal distributions are used for both the failure threshold and environment. The error associated with the normal distribution assumption is considered well within the bounds of the overall error in the Safeguard SHAA/SHAR hardness methodology.

Computation of the P_V limits for a pair of normal distributions is provided in paragraph 5.1.2 and Appendix E.

5.1.2 Computation of P_V's for Normal Distribution

In the general case expected in SHAA/SHAR computations, two dissimilar normal distributions will overlap as shown in Figure 5-2. The abscissa is the common parameter used for comparing threshold and environment, and the ordinate is the function of this parameter as described by the normal distribution equation. Other terms on Figure 5-2 are:

$\bar{E}$ = mean of the local environment

σ_E = standard deviation of the environment

X_I = intercept of the two curves which is also E_I and T_I on Figure 5-1, Ven Diagram

A_E = probability measure for the local environment

A_T = probability measure for the threshold

σ_T = standard deviation of the threshold

$\bar{T}$ = mean of the threshold

The equation for the normal distribution is:

$$f_n(X) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(X - \bar{X})^2}{2\sigma^2}}$$

At the point of intersection (X_I) on the abscissa

$$f_n(X_E) = f_n(X_T)$$

Therefore,

$$\frac{1}{\sigma_E\sqrt{2\pi}} e^{\frac{-(X_I - \bar{X}_E)^2}{2\sigma_E^2}} = \frac{1}{\sigma_T\sqrt{2\pi}} e^{\frac{-(X_I - \bar{X}_T)^2}{2\sigma_T^2}}$$

The above equation is solved for X_I yielding:

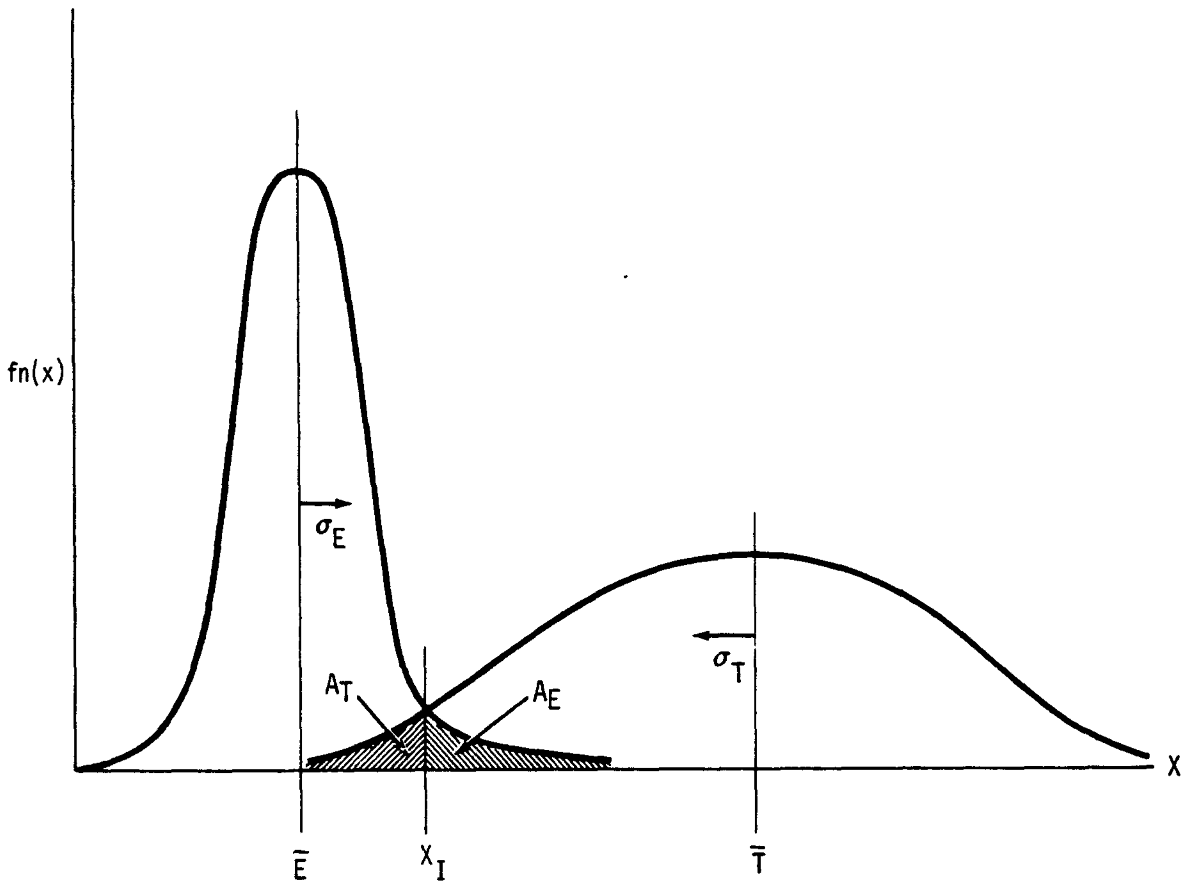

FIGURE 5-2 OVERLAP OF TWO DISSIMILAR NORMAL DISTRIBUTIONS

5.1.2 (Continued)

$$X_I = \frac{1}{\sigma_T^2 - \sigma_E^2}\left\{(\sigma_T^2\overline{X}_E - \sigma_E^2\overline{X}_T) \pm \sqrt{(\sigma_T^2\overline{X}_E - \sigma_E^2\overline{X}_T)^2 + (\sigma_T^2 - \sigma_E^2)\,[2\sigma_T^2\sigma_E^2 \,\ell n\, \frac{\sigma_T}{\sigma_E} - (\sigma_T^2\overline{X}_E - \sigma_E^2\overline{X}_T^2)]}\right\}$$

The above equation has two solutions. The value of X_I that lies between $\overline{E}$ and $\overline{T}$ is the solution required for the computation. Once X_I is determined, the areas A_T and A_E are determined. These areas are those required to compute P_V as derived in paragraph 5.1.1.

Computation of X_I, A_T and A_E by hand for each case would be time consuming with a high potential for error. To circumvent this difficulty nomographs have been prepared for computing the survival probability (P_V). The nomogrphas along with numerical examples are provided in Appendix E.

5.2 GENERAL SHAA METHODOLOGY

Items that were verified for hardness by shock tests or dynamic analyses within the TSE Shock Test Program are quantitatively demonstrated hard by the Subsystem Hardness Assurance Analysis (SHAA). Not included in the SHAA are hardness indices calculations to the in-structure response environment for items not included in the TSE Shock Test Program. Some examples are blast doors, non-MEL items (pipe supports) and non-critical equipment that must be verified against the debris forming hazard. This latter class of items receive hardness indices in the Subsystem Hardness Assurance Report (SHAR) activity, Reference 3.

All items receiving hardness indices to the in-structure response environment and verified in the TSE Shock Test Program are processed in SHAA. In other words, all item of critical TSE that can, receive hardness indices computed from data obtained from a shock test, dynamic analysis or in-place shock isolation testing are processed in SHAA.

In paragraphs 5.2.1 and 4.3 the methodology and procedures for computing hardness indices for SHAA is provided.

5.2.1 General SHAA Methodology Summary

Figure 5-3, TSE Subsystem Hardness Assurance Analysis, Logic Flow, in summary form outlines the entire SHAA process.

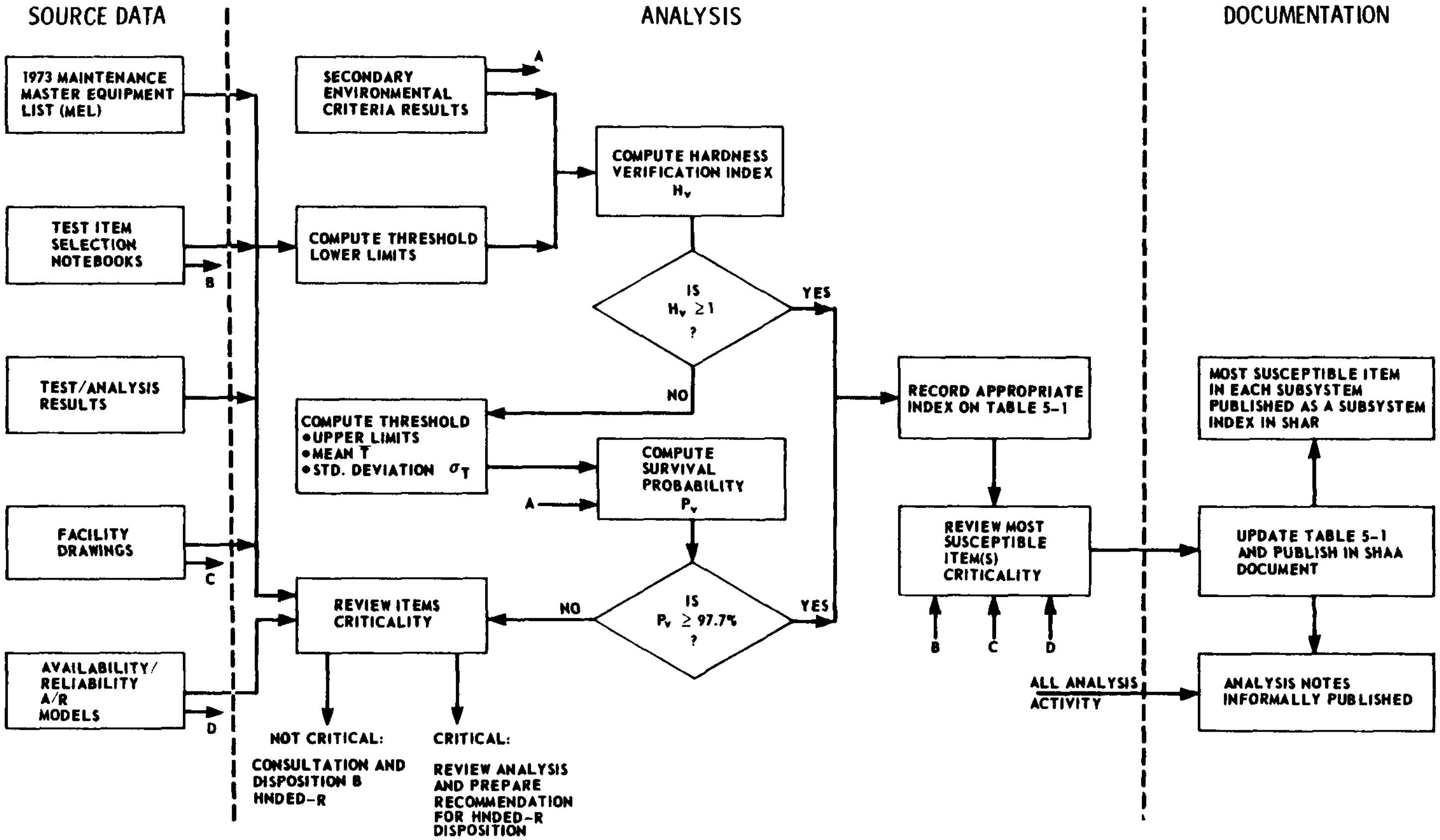

FIGURE 5-3 TSE SUBSYSTEM HARDNESS ASSURANCE ANALYSIS, LOGIC FLOW

5.2.1 (Continued)

Five data sources are used: (a) 1973 Maintenance Master Equipment List (MEL), (b) test item selection notebooks, (c) test/analysis results, (d) facility drawings, and (e) availability/reliability diagrams (A/R).

(a) <u>1973 Maintenance Master Equipment List (MEL)</u>

The MEL is a computerized listing of all TSE arranged by subsystem. Each item of equipment is identified by an Item Type Code number (ITC) and its specific location is identified by a tag number. The computer listing used for the SHAA is the 1973 Maintenance MEL. The 1973 Maintenance MEL was compiled from previous MEL listings and verified by an actual site survey. For this reason the 1973 Maintenance MEL is the most up-to-date and the most accurage source of information available for a listing of all TSE. Items not having a criticality rating in the 1973 Maintenance MEL will be processed as part of the SHAA procedure.

(b) <u>Test Item Selection Notebooks</u>

For the more complex items of TSE, the selection of items for test/analysis was accomplished by a systematic selection process described in paragraph 4.4.1, Test/Analysis Specimen Selection (Subsystem Analysis). The test item selection notebooks are the unpublished notes compiled during the selection and specification preparation.

(c) <u>Test/Analysis Results</u>

Test/analysis results are obtained from documented laboratory tests or dynamic analyses. These reports contain much of the information required in the SHAA analysis such as the actual test setup, analysis model description, input levels, functional results, and anomalies.

(d) <u>Facility Drawings</u>

Facility drawings comprise construction drawings, procurement specifications, vendor literature or other reference material that may be examined during the SHAA process.

(e) <u>Availability/Reliability (A/R) Diagrams</u>

Availability/Reliability (A/R) diagrams are flow diagrams of components within the Safeguard system constructed in a manner to

5.2.1 (Continued)

define the system reliability. The diagrams are constructed to show go, no-go relationships between components with the complex and detailed functional relationships consolidated. Series and parallel relationships are shown with an occasional interlock. Thus with the appropriate A/R diagram, a functional operation out of tolerance can be traced through the system to the WSE interface. The A/R diagrams provide an excellent check on the components criticality. As shown in Figure 5-3 the A/R diagrams are a primary data source for a criticality evaluation.

The first four data sources are used to compute the failure threshold, lower limit. These lower limits when properly combined with the secondary environmental criteria results provide the hardness verification index. The methodology for this computation is provided in paragraph 5.2.2 and the procedure is provided in paragraph 5.3. If the item shows an $H_V \geq 1$, the hardness is demonstrated and the proper notation is made in Table 5-I. An $H_V < 1$ result does not always mean the item has not met the requirement. Rather an $H_V < 1$ result means the item will require more analysis.

On Figure 5-3 the additional analysis summarized as the computation of threshold, upper limits, statistical mean of the threshold $\overline{T}$ and the statistical standard deviation of the threshold σ_T. These parameters are used with the secondary environmental criteria results to compute the survival probability P_V. The methodology for this computation is provided in paragraph 5.2.3 and the procedure is contained in paragraph 5.3. A survival probability of 97.7% or greater demonstrates hardness and the proper notation is made in SHAA document. Failure to meet the 97.7% requirement leads to criticality verification. If the item does not appear critical from this review, consultation with HNDED-R is accomplished and disposition is made per HNDED-R direction. If the item is critical the SHAA analysis is reviewed and a recommendation for remedial action is made to HNDED-R.

When all the indices are recorded for a subsystem SHAA the most susceptible item(s) for each subsystem are reviewed for criticality thus verifying that the most susceptible item is critical. When this analysis is completed the hardness index of the most susceptible item becomes the rating for the subsystem and is documented in the Subsystem Hardness Assurance Report (SHAR).

5.2.2 SHAA Computation for H_V

In paragraph 5.1, the hardness verification index was established as the first SHAA/SHAR screening equation. The hardness verification index (H_V) is defined as:

$$H_V = \frac{\bar{T} - 3\sigma_T}{\bar{E} + 3\sigma_E} \quad \text{Threshold and environment in consistent units}$$

where

$\bar{T} - 3\sigma_T$ = any threshold computation that is at least 3σ conservative on the low side

$\bar{E} + 3\sigma_E$ = local environment that is at least 3σ conservative on the high side

and both are expressed in consistent units.

For the specific application to the SHAA, the hardness verification index equation is rewritten in the following form with both the numerator and denominator in deminsionless form:

$$H_V = \frac{\prod_{1}^{4} f_{n_L}}{\frac{\bar{E} + 3\sigma_E}{S}}$$

where

S = local in-structure response environment in inches, velocity or acceleration

f_{n_L} = four lower limit independent threshold factors

$\bar{E} + 3\sigma_E$ = local environment in inches, velocity or acceleration

The local environments, S, is the in-structures shock response spectra documented in Sections 4, 5, and 6 of Volume II, Reference 1. Spectra in Sections 4, 5, and 6 are the shock response spectra derived by each AE for various locations in the hardened structures. It should be emphasized that S is not the test environment, but is the environment computed by the AE's and used for facility design. The secondary

5.2.2 (Continued)

environmental criteria limits in units are normalized to the local environment (S) in the same units. After normalizing the secondary environment criteria limits about S the hardness verification index equation reduces to:

$$H_V = \frac{\prod_{1}^{4} f_{n_L}}{\overline{E} + 3\sigma_E}$$

where $\overline{E} + 3\sigma_E$ is normalized about S.

For convenience, normalized $\overline{E}$ and σ_E values are recorded on each applicable spectra plot in Volume II, Reference 2.

For any specific equipment item, there are four independent elements that influence the hardness index. These four elements for hardness verification are:

(a) Test/analysis environment

(b) Test/analysis specimen selection

(c) Test/analysis setup and execution

(d) Test/analysis results

These four independent elements are evaluated by non-dimensional factors f_1, f_2, f_3 and f_4 which correspond to the above elements and are:

f_1 dimensionless ratio of actual test/analysis environment (S) at the actual location of the specific item

f_2 test/analysis selection factor

f_3 test/analysis setup and execution factor

f_4 test/analysis results factor

The hardness index threshold statement is written in a form so that all factors are one for perfect, greater than one for conservative and less than one for unconservative.

5.2.2 (Continued)

The factor f_1 is the ratio of the actual test/analysis environment to the evaluated local environment.

Since every item of TSE will be assigned an index in SHAA, a selection factor will be assigned for each item including items not tested or analyzed. The selection factor is f_2. From a review of the test item selection notebook, each non-tested item is rated quantitatively against the test/analysis item.

A test or an analysis nearly always contains compromises. These compromises are evaluated by factor, f_3. Compromises, especially in a test, are conservative equally as often as unconservative.

Finally a factor is assigned to the test results. This is factor f_4. For cost reasons, most of the tests are go, no-go. Go, no-go means that the specimen is subjected to the test environment and that performance is monitored. If the failure is judged serious, remedial action is taken immediately and the specimen retested. A functional deviation during test is evaluated by reference to the A/R diagram. The factor f_4 will often have a numeric value of 1. However, the option is open to assign a factor less than 1 to describe a minor failure. The overall hardness index can then support rationale for passing the item.

5.2.3 Interpretation of the SHAA Hardness Verification Index

The development in this paragraph is intended only to provide an interpretation of the SHAA results when the detail procedure in the subsequent paragraph 5.3 is followed.

Using the expanded notation for the numerator and writing the secondary environmental limits in non-normalized form the hardness verification index equation for SHAA is:

$$H_V = \frac{(f_{1L} \cdot f_{2L} \cdot f_{3L} \cdot f_{4L})}{\dfrac{(\bar{E} + 3\sigma_E) \text{ in units}}{(S) \text{ in the same units}}}$$

Of all the f factors only f_1 is a ratio of physical quantities. All the other factors determined in the dimensionless domain. By definition:

$$f_{1L} = \frac{\text{Achieved Lower Test Level}}{S}$$

5.2.3 (Continued)

For f_{1L}, the lowest test level ratio to the local environment is computed regardless of frequency.

$$H_V = \frac{\dfrac{\text{(Achieved Lower Test Level)}}{S} \; f_{2L} \cdot f_{3L} \cdot f_{4L}}{\dfrac{\bar{E} + 3\sigma_E}{S}}$$

where

$\bar{E} + 3\sigma_E$ = upper limit local environment evaluated in secondary environmental criteria with units

S = local environment documented Volume II

From the above equation S cancels leaving:

$$H_V = \frac{\text{Achieved Lower Test Level}}{\bar{E} + 3\sigma_E} \; f_{2L} \cdot f_{3L} \cdot f_{4L}$$

The hardness verification index (H_V) becomes the ratio of the actual test level to the upper limit of the local environment and then modified by selection considerations, test setup aspects and the test results. In the actual procedure, paragraph 5.3, both the threshold and environment are normalized above S which is equivalent to the result presented in this paragraph.

5.2.4 SHAA Computations for P_V

In paragraph 5.2.2 the computation of the hardness verification index was presented. The hardness verification index was defined as:

$$H_V = \frac{\prod_{1}^{4} f_{nL}}{\bar{E} + 3\sigma_E} = \frac{\bar{T} - 3\sigma_T}{\bar{E} + 3\sigma_E} \quad \text{Threshold and environment normalized}$$

It was also stated in paragraph 5.2.1 that no additional analysis is required if $H_V \geq 1$.

5.2.4 (Continued)

The computation in this paragraph is addressed to those items which failed to pass the $H_V \geq 1$ screening. For item having an $H_V < 1$, the proof of hardness is provided by the survival probability (P_V), where the survival probability is defined as the probability that the real threshold exceeds the real local environment.

In computing P_V, a ratio of some unidentified statistical threshold to some unidentified statistical environment is implied but not specifically defined. Instead of using a ratio representation, the survival probability is computed by considering a pair of dissimilar and overlaping normal distributions, paragraph 5.1.3, Figure 5-2.

$$\text{Survival probability} = P_V = P(T/L \geq 1) = \phi(\bar{T}, \sigma_T, \bar{E}, \sigma_E)$$

where

ϕ = some function of

$\bar{T}$ = mean of the threshold

σ_T = standard deviation of the threshold

$\bar{E}$ = mean of the local environment

σ_E = standard deviation of the local environment

Technically the procedure used to compute P_V is to first determine the intercept of the two normal distributions, then, determine the overlap areas A_T, A_E and finally compute the two limits of the survival probability.

$\bar{T}$ and σ_T are determined from the SHAA analysis. $\bar{E}$ and σ_E are taken from the secondary environment criteria results. The intercept of the two normal distributions (X_I) is computed from the equation derived in paragraph 5.1.2. The two areas (A_E, A_T) were obtained from widely published tables of the normal distribution. Using the overlap areas, the two limits of P_V can be computed from the expression:

$$(1 - A_T A_E) > P_V > [1 - (A_T + A_E - A_E A_T)]$$

The above expression is derived in paragraph 5.1.1.

Since the survival probability (P_V) is not deterministic but can be any value within the limits shown above, the lower limit or most con-

5.2.4 (Continued)

servative described by the expression on the right is used for SHAA/SHAR. This decision introduces some conservatism in the process. Once the values of P_V are obtained and the lower value is greater than 97.7%, the item can be documented as hard as follows:

$H = 1$

P_V = value computed

The procedure for computing $\overline{T}$, and σ_T are provided in paragraph 5.3.

Local environment parameters $\overline{E}$ and σ_E are obtained directly from secondary environmental criteria, Reference 6, and the applicable shock spectra in Volume, Reference 2.

Computation of P_V is accomplished by using these values and the nomographs provided in Appendix E.

5.3 SHAA RESULTS DOCUMENTATION AND COMPUTATION PROCEDURES

In addition to computing a hardness number for each item/subsystem, it is required that results be documented and provisions made for future technical traceability. To achieve this goal the format for providing results and the procedures to be followed are delineated in some detail in this paragraph. All of the discussion in this paragraph is addressed to specific notations to be made on Table 5-I, TSE Shock Test Program Results (SHAA). Table 5-I, when completed for each critical subsystem, will provide subsystem ratings for SHAR, each items hardness rating and references to technical traceability.

On Table 5-I there are five major subelements: (a) Heading, (b) Item Identification, (c) Threshold Limits, (d) Secondary Environmental Limits and (e) Hardness Indices. A column by column procedure for presenting the results will be provided under each major subelement.

(a) Heading

In order to be compatible with the SHAR, the detail hardness data on Table 5-I are compiled by subsystems as defined in the 1973 Maintenance MEL. The Heading on Table 5-I provides two sets of information. The first set provides the identification of the subsystem by Master Control Number (MCN), name of the subsystem and the subsystem criticality. After all of the critical items in a subsystem have been quantified, the subsystem hardness

SUBSYSTEM MCN ____________

WEAPON EFFECTS CRITICALITY ____________

SUBSYSTEM HARDNESS RATINGS [illegible] H_V ______, or P_V = ______ FOR ITC ______

[illegible] H_V ______, or P_V ______ FOR ITC ______

ITEM IDENTIFICATION					THRESHOLD LIMITS										SEC ENV LIMITS		HARDNESS INDICES	
ITC	NAME & TAG NUMBER	[illegible] CRIT	QUAN	ENV CODE	[illegible] REF	f1	T/A CODE	VS	f2	f3	f4	$\bar{T}$	σ_T	$\bar{T}$	σ_T	H_V	P_V Prob (H≥1)

TS = TEST SPECIMEN TAS = TEST ANALYSIS SPECIMEN VS = VERIFIED SPECIMEN THAT QUALIFIES THE ISG ITEM

AS = ANALYSIS SPECIMEN ISG = ITEM IN A SPECIMEN GROUP

* NOT REQUIRED FOR H_V COMPUTATION $(\bar{T} - 3\sigma_T) = \frac{4}{1} f_n(\text{lower})$

** NOT SHOWN WHEN P_V IS USED TO DEMONSTRATE HARDNESS

*** NOT REQUIRED WHEN $H_V \geq 1$ P_V MUCH GREATER THAN REQUIRED

TABLE 5-I TSE SHOCK TEST PROGRAM RESULTS

5.3 (Continued)

indices are added to the Heading along with the controlling item.

(b) Item Identification

The five columns under Item Identification provide pertinent data for each ITC in the subsystem. All data under Item Identification except environmental codes are extracted directly from the Master Equipment List (MEL) and modified as necessary from other sources.

For maximum confidence, hardness verification is required for all weapon effects criticality A and B items. For minimum cost, items having a criticality C are not evaluated for hardness except for debris forming potential. In order to fulfill these two basic principles, the Master Equipment List (MEL) has been extensively used in the TSE Shock Test Program as well as other operating programs. The MEL used for the TSE Shock Test Program SHAA is the 1973 Maintenance MEL. Listed in Table 5-I are items from the MEL with criticalities A, B and no criticality identification. Subsystem listings from this maintenance MEL are provided in Appendices A, B and C as follows:

Appendix A	PAR Site
Appendix B	MSR Site
Appendix C	RLS Site

The complete 1973 Maintenance MEL was finalized and available for use by 14 August 1973*. Although the MEL was not intended to be hardness verification tool, it does provide the best source for a listing of all items and with their criticality rating. A column-by-column description follows for the columns under Item Identification:

ITC - This is the Item Type Code. It is an alpha-numeric number assigned by USAEDH to identify each unique item of TSE. The ITC number is universally used throughout the Safeguard System to identify individual items.

* Final approval/assignments of Weapon Effect Criticality to all subsystems and items by USAEDH is not expected until October 1973.

5.3 (Continued)

Name and Tag Numbers - The generic name of each ITC is recorded in this column. In order to preserve consistency with the MEL, the generic name is presented exactly (including abbreviations) as it appears in the MEL. Since the generic name is not standardized in industry, slight variations in name may appear for basically the same item. This has been taken into account in the subsystem analysis. Each tag number (facility location number) of an ITC should be listed separately if its environmental code is different from others of the same ITC number or the item has a unique mounting arrangement. In preparing data for Table 5-I, one line is used when the following conditions are met:

(1) Same ITC number
(2) Same environmental code
(3) Same general mounting

If the above three conditions are met, several items can be grouped on one line. This will assure that the correct environment is used when subsequent analyses are performed to determine the item's hardness.

Criticality - This is the weapon system criticality. By definition the TSE Shock Test Program is addressed only to criticality A and B items. During the subsystem analysis, items identified in the MEL as criticality A and B were emphasized. In Table 5-I all items with a criticality A and B as defined by the MEL and those with an unassigned criticality are listed. Criticalities are automatically reviewed in the SHAA when an item has a low hardness index as described in paragraph 5.2, and Figure 5-2. If a criticality is changed, the notation will be made in this column. For example, the notation ~~B~~, C means the criticality was changed from B to C. Rationale for the change is contained in the work notes. Criteria for designating an item as critical in the SHAA is as follows: Any item whose function wither directly or indirectly supports the weapon system/attack capability is critical. As shown on Figure 5.2 the A/R diagram is used as one data source to establish criticality from the criteria listed above.

Quantity - When more than one item of a specific ITC fulfills the criteria of same ITC, same environmental code, and same general mounting, the quantity is entered in this column.

5.3 (Continued)

Environmental Codes - Each floor, wall, ceiling of each facility has been given an alpha-numeric code which identifies the appropriate shock spectra in Volume II, In-Structure Shock Spectra, Reference 2.

(c) Threshold Limits

The Threshold Limits major heading contain the summary results from the threshold calculations. The procedure that will be used to compute the summary results under each column heading is discussed below:

Test Reference - This column references the test/analysis report prepared by the test laboratory or the analyst. Contained in the test report is much of the information required for the threshold calculation.

f_1 Environment Factor - Using the test/analysis level actually achieved, which is documented in the test reference, the environment factor f_1 is computed. Two numbers identify the environment factor and are inserted in this column after each ITC. The first number is the lower value and the second is the upper value. If the two computed f_1 factors are 0.8 for the lower and 1.2 for the upper, the notation in this column is 0.8-1.2.

The environment factor lower limit is computed at the critical frequency of the item. If the items' critical frequencies are not known, the ratio used for computing the lower limit of f_1 is the smallest ratio of the achieved environment divided by the local environment over the range of frequencies corresponding to the item's critical frequencies.

Figure 5-4, Environmental Factor f_1 Example, presents an actual SHAA calculation. It should be noted that on Figure 5-4 more than one shock was applied to the item. In computing the f_1 factor, the highest level actually achieved during test is used for the f_1 evaluation. For the example shown on Figure 5-4, the minimum ratio is circled at 50 Hz. The upper value of f_1 is the largest ratio of achieved environment regardless of the frequency. The maximum ratio for this example is found at 500 Hz, Figure 5-4.

If an analysis is performed, the critical frequencies are known. The environment factor for the lower limit f_1 is then the smallest

LOWER LIMIT f_1:

(f_1) IS DETERMINED BY FINDING THE SMALLEST RATIO OF THE HIGHEST ACHIEVED TEST LEVEL OVER THE ENVIRONMENTAL CODE AT THE ITEM LOCATION OVER ALL TEST FREQUENCIES AND ALL TEST AXES.

UPPER LIMIT f_1:

(f_1) IS DETERMINED BY FINDING THE LARGEST RATIO OF THE HIGHEST ACHIEVED TEST LEVEL OVER THE ENVIRONMENTAL CODE AT THE ITEM OVER ALL TEST FREQUENCIES AND ALL TEST AXES.

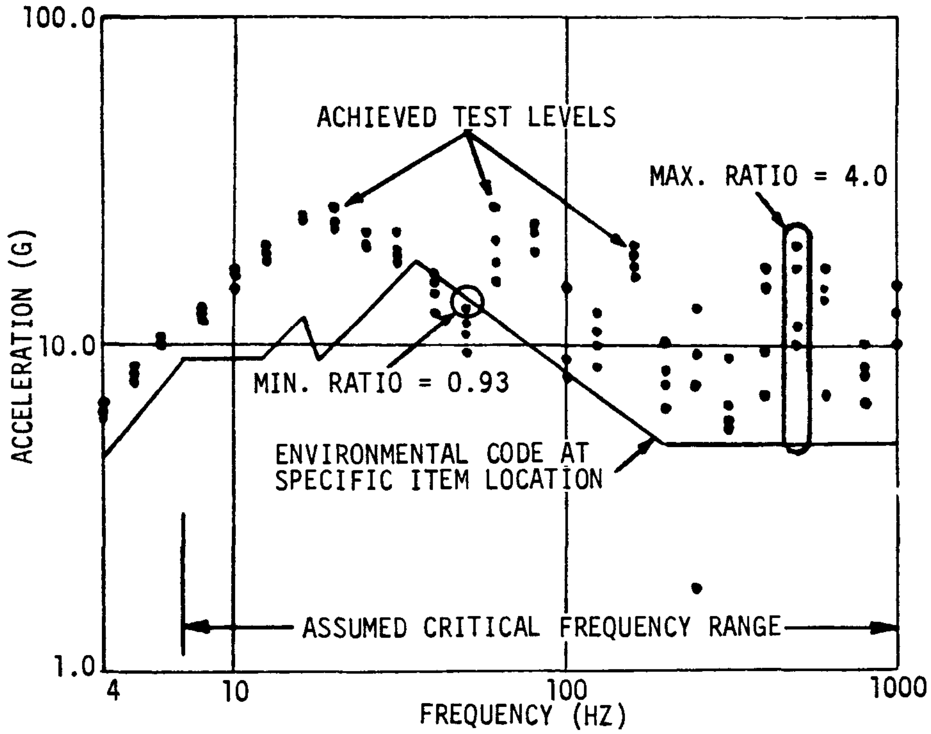

FIGURE 5-4: ENVIRONMENT FACTOR f_1 EXAMPLE

5.3 (Continued)

of the ratios of the analysis input environment over the local environment for each critical modal frequency determined by the analysis. For analysis considerations, the upper limit f_1 is identical to lower limit f_1 because the critical frequencies are precisely known.

It should be emphasized that f_1 is computed by using the actually achieved test/analysis environment and the local environment. The actually achieved test/analysis environment is obtained from the test report which is referenced in the test reference column. The local environment is obtained from Volume II of this document, Reference 2. The environment code used to identify the applicable local environment is recorded in the previous column.

In many instances the item being evaluated is installed on shock isolation systems, but was tested in the hardmounted configuration. The difference in test environment and actual environment can be accounted for in either the f_1 factor or the test set-up and execution factor (f_3). At the discretion of the evaluator action can be taken to either account for the transmissibility effects of the isolation system in f_1 or the approach for reduced flexibility described under f_3 can be applied.

The normalized secondary environmental criteria data are included on the spectra plots in Volume II, Reference 2. It would be convenient to enter the $\bar{E}$ or σ_E on Table 5-I at this time. The specific SEC data to be entered on Table 5-I are those that correspond to the frequency that determined the f_1 (lower limit).

T/A Code and VS - Before computing the f_2 selection factor, two columns are used to record decisions previously made during the subsystem analysis. The first column (T/A Code) identifies the disposition of the item. This column describes by code the decision made during the selection process or subsystem analysis for each item in Table 5-I. The codes are:

- TS = specimen tested
- AS = specimen analyzed
- TAS = specimen both tested and analyzed (structurally analyzed and funtionally sensitive parts tested)
- ISG = item was not tested or analyzed and is a member for a group which is represented by one or more tested items.

5.3 (Continued)

For every item that was identified as ISG, the tested or analyzed specimen(s) that provides the verification data must be identified. In the column identified as VS (verification specimen), the ITC number(s) of the tested or analyzed specimen(s) is entered. For test and/or analysis items, there is no notation under VS.

f_2 Selection Factor - Selection factors f_2 are recorded in the next column. The lower limit is recorded first and the upper limit second.

The lower and upper limit of the selection factor compares the shock sensitivity of the item being evaluated to the item tested or analyzed. For a tested or analyzed item, lower limit f_2 and upper limit f_2 are identical and equal to one. A $f_2 = 1$ is automatically applied to TS, AS and TAS items because the item is exactly represented by itself. For the ISG items (representative items), an evaluation of the items relative shock susceptibility to the item tested or analyzed is made. Evaluation of lower limit f_1 and upper f_1 is accomplished using the guidelines provided in Table 5-II. These guidelines provide consistency in judgment among the personnel performing the analysis.

The Table 5-II, Selection Factor (f_2) Guidelines, provides a list of reasons for ating an ISG item "better than" or "not as good as" the item tested or analyzed. Accompanying each reason is a lower and upper limit for a subfactor. The subfactors are added algebraically to one to form the lower and upper limit of f_2.

f_3 Test Setup and Execution Factor - The test setup and execution factor (f_3) provides a rating covering the test/analysis compromises. This factor quantitatively rates how well the test or analysis was executed and how well test mounting conditions represent the actual installed conditions. The rating for the test f_3 is based on the guidelines in Table 5-III, Test Setup and Execution Factor (f_3) Guidelines, and Figure 5-5, Installation Simulation Subfactor, to assure consistency among personnel. Table 5-III contains the guidelines and accompanhing subfactors for determining the f_3 test setup and execution factor. The subfactors are added algebraically to one to form the lower and upper limit of f_2. Guideline 1.2 in Table 5-III refers to Figure 5-5 and provides a method for determining the effect of a mounting having a significant stiffness difference such as local shock isolation. (Note that the effects of shock isolation systems

	GUIDELINES	SUBFACTOR (SF) LOWER	UPPER
1.0	Item is a tested specimen.	0	0
2.0	Item is not a tested specimen - use 2.1, 2.2, 2.3, and 2.4 or 2.5.		
2.1	Item under consideration similar to tested item except for size. Choose one of the following (see 2.1.1 thru 2.1.6).		
2.1.1	Item under consideration same type plus similar capacity/size to tested item or bracketed by capacities/sizes of tested items.	0	0
2.1.2	Item under consideration somewhat smaller than tested item.	+0.05	+0.05
2.1.3	Item under consideration considerably smaller than tested item.	+0.10	+0.10
2.1.4	Item under consideration somewhat larger than tested item.	-0.05	0
2.1.5	Item under consideration considerably larger than tested item.	-0.10	0
2.1.6	Item under consideration radically larger than tested item.	-0.15	-0.05
2.2	Item under consideration has mounting which compares as follows to tested specimen (see 2.2.1 thru 2.2.3):		
2.2.1	Item under consideration mounted similar to tested specimen.	0	0
2.2.2	Item under consideration has more rigid mounting than tested	-0.05	0
2.2.3	Item under consideration has less rigid mounting than tested specimen.	+0.05	+0.05

TABLE 5-II: SELECTION FACTOR (f_2) GUIDELINES

	GUIDELINES	SUBFACTOR (SF) LOWER	SUBFACTOR (SF) UPPER
2.3	Complexity of untested item relative to tested item. Use one of following three (2.3.1, 2.3.2, or 2.3.3):		
2.3.1	Both of similar degree of complexity.	0	0
2.3.2	Untested item more complex.	-0.05	0
2.3.3	Untested item less complex.	+0.05	+0.05
2.4	All critical components under consideration in item are identical to those in a tested specimen AND critical components mounting are as follows (see 2.4.1, 2.4.2, 2.4.3):		
2.4.1	Critical components are mounted similar to those in tested specimens.	0	0
2.4.2	Critical components have more rigid mounting than those in tested specimen.	-0.05	0
2.4.3	Critical components have less rigid mounting than those in tested specimen.	+0.05	+0.05
2.5	One or more critical components in item are not in or identical to components in a tested specimen. Each component is considered separately, lowest component factor will be f_2 for item (use 2.5.1, plus 2.5.2, 2.5.3, and 2.5.4).		
2.5.1	Untested component similar to tested component. Pick one of following five for degree of similarity:		
2.5.1.1	Same type of component PLUS similar capacity/size to tested component or bracketed by capacities/sizes of tested components. EXAMPLE: Same part number but different dash number or different (but close) range.	0	0

TABLE 5-II: SELECTION FACTOR (f_2) GUIDELINES (Continued)

	GUIDELINES	SUBFACTOR (SF) LOWER	SUBFACTOR (SF) UPPER
2.5.1.2	Slightly different type but same capacity/size as tested component; OR same type but considerably different capacity/size than tested component. EXAMPLE: Different part number, but same capacity and method of operation; OR same part number but much different capacity.	-0.05	0
2.5.1.3	Slightly different type and capacity/size than tested component. EXAMPLE: Different part number, different capacity, but same method of operation.	-0.10	0
2.5.1.4	Considerably different type and capacity/size from tested component. EXAMPLE: Different part number, different method of operation, but same function.	-0.15	-0.1 to 0
2.5.1.5	No representative component tested.	-0.25	-0.25 to 0
2.5.2	Untested critical component mounting, use one of following three (delete this factor if 2.5.1.5 above was chosen):		
2.5.2.1	Untested component mounting similar to tested component mounting.	0	0
2.5.2.2	Untested component mounting more rigid than tested component mounting.	-0.05	0
2.5.2.3	Untested component mounting less rigid than tested component mounting.	+0.05	+0.05
2.5.3	Complexity of untested component relative to tested component, use one of following three (delete this factor if 2.5.1.5 above was chosen):		

TABLE 5-II: SELECTION FACTOR (f_2) GUIDELINES (Continued)

	GUIDELINES	SUBFACTOR (SF) LOWER	UPPER
2.5.3.1	Both of similar degree of complexity.	0	0
2.5.3.2	Untested component more complex	-0.05	0
2.5.3.3	Untested component less complex.	+0.05	+0.05
2.5.4	Confidence in selection analysis of untested component, use one of following two:		
2.5.4.1	Untested component is simple and rugged.	0	+0.05
2.5.4.2	Untested component is fragile and/or complex.	-0.05	0

f_2 = 1 + SF of paragraph 1.0 above (tested item)

OR f_2 = 1 + ΣSF's of paragraphs 2.2, 2.3, and 2.4 above (all critical components tested)

OR F_2 = 1 + ΣSF's of paragraphs 2.1, 2.2, 2.3, and 2.5 above (all other items).

TABLE 5-II: SELECTION FACTOR (f_2) GUIDELINES (Continued)

	GUIDELINES	SUBFACTOR (SF) LOWER	SUBFACTOR (SF) UPPER
1.0	Dynamic simulation of actual installation - pick one of the following four:		
1.1	Exact duplication.	0	0
1.2	If a mounting change is judged significant and stiffness dimensions are available, the effect of the stiffness change can be computed. Figure 5-4 is an example.	See text and Figure 5-5	See text and Figure 5-5
1.3	If a stiffness increase does not warrant a computation (1.2), or is non-computable.	0 to 0.20	0 to 0.20
1.4	If a stiffness decrease does not warrant a computation (1.2), or is non-computable.	0 to -0.20	0
2.0	Deleted		
3.0	Funcational monitoring - pick one of the following three:		
3.1	All actual input parameters applied: i.e., voltages pressures, or flows; and representative functions monitored at least one of each type of component monitored.	0	0

TABLE 5-III TEST SETUP AND EXECUTION FACTOR (f_3) GUIDELINES

	GUIDELINES	SUBFACTOR (SF) LOWER	UPPER
3.2	Representative critical functions monitored only, at least one of each type of component; for example, continuity checks only, low pressures, or no flow.	-0.5	0
3.3	Monitor some critical functions only, not all types of components monitored.	-0.05 to -0.20	0

EQUATION FOR f_3

$$f_3 = 1 + \sum (\text{SF's } 1, 2, 3 \text{ above})$$

TABLE 5-III TEST SETUP AND EXECUTION FACTOR (f_3) GUIDELINES (Continued)

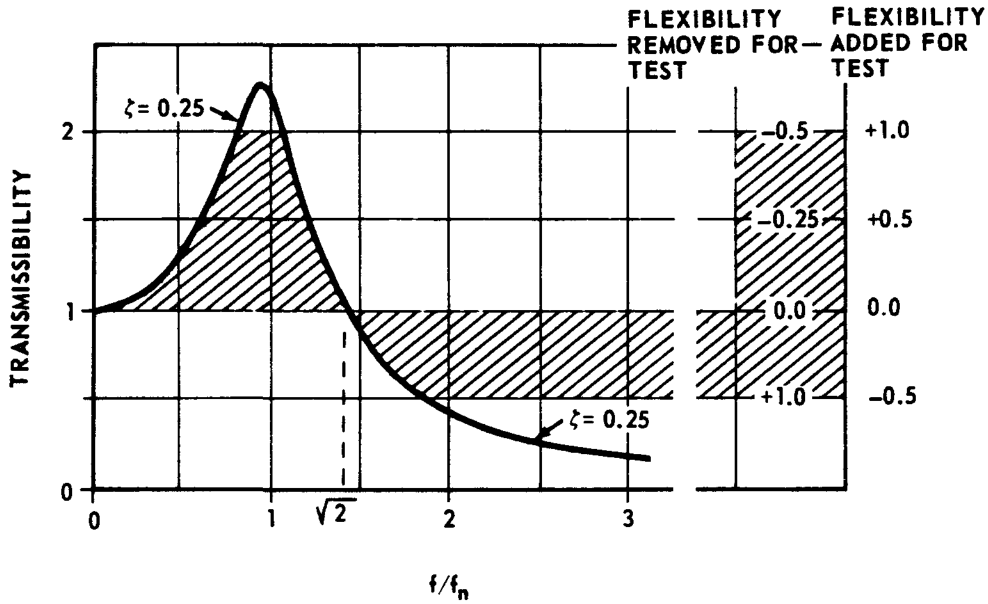

FIGURE 5-5 INSTALLATION SIMULATION FACTOR

5.3 (Continued)

can be accounted for either in the f_3 or f_1, the test analysis environment factor.)

In using Figure 5-5 the first consideration is to determine if significant flexibility was removed for test or to determine if significant flexibility was added for test. An example of flexibility removed for test is an item locally shock isolated in the facility, but for the test the isolators were removed and the item was tested hard. Added flexibility for test is not expected to be as common, but the case is included in event the practical considerations for a test requiring the use of a flexible mounting are encountered. In any event, if the change in flexibility is deemed significant, guideline 1.2, the following discussion, and Figure 5-5 are used. If the change is not deemed significant, guidelines 1.3 and 1.4 are used.

For application of guideline 1.2, the first step is the computation of the removed or added flexibility (K). Admittedly the other stiffness effects are ignored which is to say the removed or added flexibility dominates the fundamental mounting frequency. Guideline 1.2 is valid only when this is true and the removed or added flexibility dominates. Otherwise guidelines 1.3 and 1.4 are used.

Using the removed or added spring constant (K) and the supported weight, the natural frequency of the mounting is computed. Let this frequency be f_n.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{Kg}{w}}$$

w = weight of the item

The next step is to establish a range of frequencies that is likely to effect the structural integrity or functional performance of the item. Let this frequency range be f.

Using f_n and f the ratio f/f_n is computed and compared with $\sqrt{2}$. The number $\sqrt{2}$ is the abscissa on the classical transmissibility plot where the transmissibility is one.

In computing the ratio f/f_n consideration should be given to the fact that f is a range rather than a deterministic number.

5.3 (Continued)

In order to cover all the possibilities, all four combinations of f/f_n ratios and flexibility changes are discussed. Let these four combinations be cases I through IV as follows:

Case I Flexibility Removed, $f/f_n > \sqrt{2}$

Case II Flexibility Removed, $f/f_3 < \sqrt{2}$

Case III Flexibility Added, $f/f_n > \sqrt{2}$

Case IV Flexibility Added, $f/f_n < \sqrt{2}$

Subfactors for f_3 under guideline 1.2 are obtained directly from Figure 5-5 for all the above four cases. Figure 5-5 is a classical transmissibility plot for a system having damping 0.25 of critical. Added to the transmissibility plot are shade areas. These shaded areas represent the limits on the subfactors to be used in SHAA.

Following is a short discussion of each case in relationship to the transmissibility plot in Figure 5-5.

Case I - Flexibility Removed, $f/f_n > \sqrt{2}$ - For this case the critical frequencies are above $\sqrt{2}$ and are effectively isolated by the mounting in the facility. But the isolation was removed for the test and the f_3 factor can be increased. The upper limit of the f_3 subfactor is one as shown on Figure 5-5. The lower limit subfactor is zero.

Case II - Flexibility Removed, $f/f_n < \sqrt{2}$ - When $f/f_n < \sqrt{2}$ the critical frequencies in the item are very low and within the resonance range of the more flexible mounting in the facility. The mounting used in the test does not excite these frequencies to the extent experienced in the facility. For this case the lower subfactor is read from the transmissibility curve to a minimum of -0.5. The upper limit subfactor is zero.

Case III - Flexibility Added, $f/f_n > \sqrt{2}$ - For this case the items critical frequencies are above $\sqrt{2}$ and isolated during the test. Since the facility mounting does not provide the same isolation, the subfactor for the lower limit is negative. The lower limit of the subfactor is read from the curve to a minimum of -0.5. For the upper limit the subfactor is zero based on the

5.3 (Continued)

rationale that the change in mounting does not effect the items' structure and performance.

Case IV - Flexibility Added, $f/f_n < \sqrt{2}$ - When $f/f_n < \sqrt{2}$ the item's critical frequencies are within the resonance region of the flexible mounting. If the flexibility is added for the test these frequencies are excited more during test and the resulting subfactors are positive. The upper limit of subfactor is read from the curve with a maximum of +1.0. For the lower limit zero is used.

The assignment of the lower limit and upper limit f_3 factor for an analysis is different and more detailed than the assignment for a test. The factor f_3 must be determined on an individual basis. Five major points are considered for the analysis f_3 upper and lower factors.

(1) Simulation of installation, or how close the analysis model simulates actual mounting conditions.

(2) Input environment, whether the inputs were uni- or multi-axis.

(3) Dynamic characteristics simulation, or the estimated agreement of modal frequencies and mode shapes between the analysis model and the actual item.

(4) Specimen monitoring, or whether the critical locations on the specimen are included in the analysis so failure can be noted.

(5) Dynamic simulation, or a rating of the quality of the dynamic response analysis. The last point quantitatively answers such questions as: (a) how well were the inputs from 1, 2, 3 above included? (b) how good is the calculation of dynamic response? (c) how good is the estimation of possible collision forces? (d) how good is the representation and analysis of external appurtenances?

Some examples of (a) through (d) are as follows: (a) includes such items as estimating the importance of the modes selected to be included (or excluded), or the loss of accuracy by excluding very high frequency modes or very stiff components, (b) includes estimations of loss of accuracy due to noise (in an analog com-

5.3 (Continued)

puter), round-off, or mathematical techniques used for solutions of equations, (c) may include rating the accuracy of plastic or elastic deformation estimations, (d) may be an estimate of accuracy loss due to including in the analysis an insufficient length of stiff conduit or pipe feeding the item under analysis. Each of these considerations are evaluated for both the lower and upper limits, and combined to form a lower and upper limits for f_3.

As was done previously, both the lower and upper limits are recorded in this column.

<u>f_4 Results Factor</u> - Test or analysis results provide the last lower and upper f_4 factor. This factor quantitatively rates how well the specimen and the items it represents fared during test or analysis.

Testing in Safeguard was conducted generally as go or no-go situation with a failure meaning f_4 is zero and a successful test meaning f_4 should be equal to or even greater than one. An evaluation is usually possible for a rating greater than one as a result of applying the guidelines in Table 5-IV, Test Results Factor (f_4) Guidelines. Guidelines for f_4 in Table 5-IV are not formatted as lower and upper subfactors for each guideline as was done for the previous guidelines. Instead only one guideline is used to describe the result and accordingly Table 5-IV is formatted to read directly the f_4 upper and lower factor.

In the event that the test shows some performance degradation or other anomaly which may not necessarily cause a failure, a factor for f_4 between zero and one could be assigned. The magnitude would be based on the estimated probability that the anomaly would cause a mission failure. These possibilities are provided in Table 5-IV guidelines.

For an analysis the f_4 factors are the minimum and maximum factor of safety from all critical locations on the analysis specimen. For analysis f_4 (both lower and upper) can be much greater than one. As was done on previous (f) factors, both the upper and lower values are recorded in this column.

At this point the computation of the hardness verification index H_V is performed.

	GUIDELINES	VALUE OF f_4 LOWER	UPPER
1.0	Item is a tested specimen - pick one of the following four:		
1.1	No failures of any components or structure plus all component types in item are also in at least two other test specimens and at least 15 of each distinct type of component were tested.	1.15	1.15
1.2	No component or structural failures but other conditions in 1.1 not met.	1.0	1.0 to 1.15
1.3	A failure occurred - NOTE: Failure occurrence must be noted during SHAA for each component exchibiting an anomaly (failure is defined as an anomaly which could cause mission loss).	0	0
1.4	An anomaly occurred which may cause mission loss. Failure in this case is ill-defined and the probability that the anomaly will cause a mission loss must be estimated.	determine on a case basis in coordination with HND	1.0
2.0	Item is not a tested item but represented by a tested item, pick one of the following four:		
2.1	No failures of any components or structure in tested representative item plus all component types in item are also in at least three test specimens and at least 15 of each distinct type of component were tested.	1.15	1.15

TABLE 5-IV TEST RESULTS FACTOR (f_4) GUIDELINES

	GUIDELINES	VALUE OF f_4 LOWER	UPPER
2.2	No failures of any components or structure in tested representative item but other conditions of 2.1 are not met.	1.0	1.0 to 1.15
2.3	A failure occurred in tested representative item. This failure must be in tested components or structure duplicating or representing components or structure in represented item. Failures in non-representative parts of tested item do not affect represented item. NOTE: Failure occurrence must be noted during SHAA.	0	0
2.4	An anomaly occurred in tested representative item which may cause mission loss if it occurred in represented item, probability of mission loss must be estimated.	determine on a case basis in coordination with HND	1.0

TABLE 5-IV TEST RESULTS FACTOR (f_4) GUIDELINES (Continued)

5.3 (Continued)

$$H_V = \frac{f_1(\text{lower}) \cdot f_2(\text{lower}) \cdot f_3(\text{lower}) \cdot f_4(\text{lower})}{\overline{E} + 3\sigma_E}$$

The secondary environmental limits $\overline{E}$ and σ_E are recorded in the next two columns. It was suggested during the discussion of the f_1 factor that these values be entered in the secondary environmental columns when the spectra plots are used for the f_1 computation. If not they are transcribed from the local environment spectra plot identified by the environmental code under Item Identification. The secondary environmental criteria limits selected from the spectra plot should correspond to the frequency that dictated the value of f_1 lower.

The notations in the remainder of Table 5-I depend on the result of the H_V computation.

<u>Mean $\overline{T}$</u> - If $H_V \geq 1$ an asterisk, *, is entered. If $H_V < 1$ the mean $\overline{T}$ is computed as follows:

The mean ($\overline{T}$) is the mean value of the four threshold factors expressed as a product, paragraph 5.2.1 and is computed only when a computation of P_V is required.

$$\overline{T} = \left(\frac{f_{1U} + f_{1L}}{2}\right) \left(\frac{f_{2U} + f_{2L}}{2}\right) \left(\frac{f_{3U} + f_{3L}}{2}\right) \left(\frac{f_{4U} + f_{4L}}{2}\right)$$

<u>σ_T Standard Deviation</u> - If $H_V \geq 1$ an asterisk, *, is entered. If $H_V < 1$ the standard deviation σ_T is computed as follows:

The symbol σ_T is the threshold standard deviation based on the assumption that the threshold probability distribution is normal. In addition it has been shown within engineering accuracy that the product of the four lower limits of the four factors is the minus 3σ case.

By using the above two assumptions

$$\overline{T} - 3\sigma_T = \prod_{1}^{4} f_L$$

5.3 (Continued)

$$\sigma_T = \frac{\bar{T} - \prod_{1}^{4} f_{nL}}{3}$$

where

$\bar{T}$ = threshold mean

$\prod_{1}^{4} f_{nL}$ = product of the four lower limits

σ_T = threshold standard deviation

The asterisk notation in the $\bar{T}$ and σ_T columns calls attention to the fact that the item was demonstrated hard by the H_V calculation and there is no reason to separately identify the two quantities.

(d) Secondary Environmental Limits

The mean $\bar{E}$ and standard deviation σ_E for the local environment are obtained directly from information contained on each individual shock spectra in Volume II, Reference 2. These data on each shock spectra have been extracted from the prepublication Secondary Environmental Criteria results, Reference 6. The data on the shock spectra plots have been normalized about S according to the requirements in paragraphs 5.2.1 and 5.2.2.

$\bar{E}$ Local Environment Mean - On the shock spectra plots more than one $\bar{E}$ is shown. Each $\bar{E}$ applies to a frequency band that is also indicated on the spectra plot. For this column the $\bar{E}$ value that applies to the frequency band corresponding to the frequency band used for the computation of lower f_1, environment factor. The specific shock spectra plot used to obtain this value is the one corresponding to the environmental code in the last column under the major heading "Item Identification." The normalized $\bar{E}$ as recorded on the local shock spectra is defined as follows:

5.3 (Continued)

$$\bar{E} = \frac{\text{mean of the local environment in units at the frequency range used for } f_1 \text{ lower computation}}{S \text{ (in the same units)}}$$

where

S = spectra line in the frequency range used in the f_1 lower computation, Volume II, Reference 2.

<u>σ_E Standard Deviation of the Local Environment</u> - Adjacent to the notation $\bar{E}$ on the shock spectra is the normalized standard deviation σ_E for the environment. This quantity is recorded in this column. Again, the standard deviation applicable to the computation of lower f_1 is recorded. The two quantities $\bar{E}$ and σ_E complete the local environment data required for the H_V or P_V computation.

(e) <u>Hardness Indices</u>

As described in paragraphs 5.1, 5.2.1 and 5.2.2 one of two indices is used to quantitatively verify hardness. These quantities are H_V the hardness verification index or P_V the survival probability. Also it was pointed out that H_V is easier to compute, more conservative and P_V is computed only if $H_V < 1$.

<u>H_V Hardness Verification Index</u> - In paragraph 5.2.1,

$$H_V = \frac{\bar{T} - 3\sigma_T}{\bar{E} + 3\sigma_E} = \frac{\prod_1^4 f_{nL}}{\bar{E} + 3\sigma_E}$$ both numerator and denominator are normalized

where

$\prod_1^4 f_{nL}$ = product of the four lower limit f factors

$\bar{E}$ and $3\sigma_E$ = secondary environmental limits normalized about S

The quantities $\bar{E}$ and σ_E were previously recorded under the secondary environmental limits major heading.

5.3 (Continued)

If $H_V \geq 1$, the computed hardness verification index is recorded and no further analysis is required. If $H_V < 1$, a double asterisk symbol, **, is entered in this column. The symbol ** means that the H_V computation failed to demonstrate the hardness and the analysis was continued to a survival probability (P_V) computation.

P_V Survival Probability - If the hardness has been demonstrated by an H_V computation a triple asterisk symbol, ***, is entered. The symbol, ***, means that the favorable H_V computation indicates the survival probability is much greater than required.

If an item does not achieve a hardness evaluation by an $H_V \geq 1$ computation, the survival probability is computed. Technical methodology for the survival probability is contained in paragraphs 5.1.1, 5.1.3, and 5.2.2. Four parameters are required for a P_V computation. For the threshold $\bar{T}$ and σ_T are required, and $\bar{E}$ and σ_E are required for the local environment. Using these four values, nomographs and methodology in Appendix E (to be provided) are used to determine P_V. The nomographs in Appendix E determine the value of P_V with no further calculation.

If $P_V \geq 97.7\%$, the item is demonstrated hard to the requirement and the value of P_V is recorded in this column.

Finally, when all hardness indices are computed, a criticality check is accomplished. This review is performed on the most susceptible item in each subsystem (lowest H_V or P_V). If the most susceptible item is shown to be critical no further work is performed on that subsystem. If the most susceptible item is not verified as critical, consultation with HNDED-R is accomplished. This analysis is performed in order to insure that the most susceptible item in a subsystem is a "verified" criticality A or B. As a result of this criticality review, changes are made in the "W.E. Crit" column under the major heading Item Identification.

Criticality reviews are conducted by reference to the A/R diagram and by applying the criteria for criticality: "Any item whose function either directly or indirectly supports the weapon system attack capability is critical."

5.3.1 Extension to the Subsystem Level

Upon completion of the hardness evaluation for each item in the subsystem and upon completion of the criticality review of the most susceptible item(s) the hardness of the subsystem as a whole can be assigned. In the Heading the hardness index of the most susceptible critical item is recorded. This is the subsystem hardness rating. For completeness the hardness index of the least susceptible item is recorded. The subsystem hardness indices are entered in Figure 6-2 in the SHAR document, Reference 3.

APPENDIX B

DEVELOPMENT OF FRAGILITY DESCRIPTIONS BY FAILURE MODE FOR ELECTRICAL AND CONTROL EQUIPMENT

COMPUTER PROGRAM TO DERIVE CUMULATIVE DISTRIBUTION FUNCTIONS FROM HAZARD FUNCTIONS

```
C THIS PROGRAM TAKES INPUT PROBABILITY OF FAILURE DATA (C X LAMDA)
C TOGETHER WITH ACCELERATION LEVELS AND CALCULATES THE
C CUMULATIVE DISTRIBUTION FUNCTION(FRAGILITY CURVE)
C THIS PROGRAM WAS WRITTEN BY G.S. HARDY OF STRUCTURAL MECHANICS ASSO.
 PROGRAM SSMRP(INPUT,OUTPUT,TAPE8,TAPE6=OUTPUT)
C TAPE 8 CONTAINS THE INPUT ACCELERATIONS AND CORRESPONDING CONDITIONAL
C PROBABILITY OF FAILURE (C X LAMDA)
 DIMENSION X(41),Y(41),N(41),CPF(10),G(10),CDF(10),XL(10),SIGMA(10)
 DIMENSION SIGMAA(41)
 DATA (X(I),I=1,11)/0.,.5,1.,1.5,2.,2.5,3.,3.5,4.,4.5,5./
 DATA (X(I),I=12,21)/5.5,6.,6.5,7.,7.5,8.,8.5,9.,9.5,10./
 DATA (X(I),I=22,31)/10.5,11.,11.5,12.,12.5,13.,13.5,14.,14.5,15./
 DATA (X(I),I=32,41)/15.5,16.,16.5,17.,17.5,18.,18.5,19.,19.5,20./
 DATA (Y(I),I=1,41)/41*0./
 READ(8,*) MM
C MM IS THE NUMBER OF COMPONENTS WHICH WERE TESTED
 DO 1000 II=1,MM
 READ(8,*) NN
C NN IS THE NUMBER OF ACCELERATION LEVELS TO WHICH A SPECIFIC COMPONENT
C HAS BEEN SHOCK TESTED
 READ(8,*)(G(I+1),I=1,NN)
C G IS THE ACCELERATION LEVEL OF THE SHOCK TEST
 READ(8,*)(CPF(I+1),I=1,NN)
C CDF IS THE CONDITIONAL PROBABILITY OF FAILURE TIMES A CONSTANT "C"
 G(1)=0.
 CDF(1)=0.
 N(1)=1
 Y(1)=0.
 XL(1)=0.
 SIGMA(1)=0.
 IF (CPF(2).EQ.1.0) GO TO 800
 IF (NN.EQ.1.AND.CPF(2).EQ.0.) GO TO 900
 IF(CPF(2).EQ.0.0) GO TO  700
 XL(2)=-(2/(G(2)-G(1)))*ALOG(1-CPF(2))
 C=CPF(2)/XL(2)
 300 NEND=NN+1
 DO 400 I=2,NEND
 XL(I)=CPF(I)/C
C XL IS THE CALCULATED CONDITIONAL PROBABILITY OF FAILURE (LAMDA)
 SIGMA(I)=SIGMA(I-1)+XL(I-1)*(G(I)-G(I-1))+.5*(XL(I)-XL(I-1))*(G(I)-G(I-1))
C SIGMA IS THE INTEGRATED AREA UNDER THE "XL" CURVE
 CDF(I)=1-EXP(-SIGMA(I))
 400 CONTINUE
 IF(G(NEND).LT.20.0) GO TO 600
 405 PRINT 410
 410 FORMAT(/1X,T5,*SPECTRAL ACCELERATION*,T35,*C X LAMDA*,T55,*CDF*)
 DO 430 I=1,NEND
 PRINT 420,G(I),CPF(I),CDF(I)
 420 FORMAT(T5,F6.3,T35,F6.3,T55,F6.3)
 430 CONTINUE
 DO 500 I=2,41
 IF (X(I).LE.G(2)) GO TO 450
 IF (X(I).LE.G(3)) GO TO 460
 IF(X(I).LE.G(4)) GO TO 470
 IF (X(I).LE.G(5)) GO TO 480
 IF (X(I).LE.G(6)) GO TO 490
 IF (X(I).LE.G(7)) GO TO 474
 IF (X(I).LE.G(8)) GO TO 476
 IF (X(I).LE.G(9)) GO TO 478
 450 SIGMAA(I)=X(I)/G(2)*SIGMA(2)
 GO TO 495
```

```
460 SIGMAA(I)=SIGMA(2)+(X(I)-G(2))/(G(3)-G(2))*(SIGMA(3)-SIGMA(2))
GO TO 495
470 SIGMAA(I)=SIGMA(3)+(X(I)-G(3))/(G(4)-G(3))*(SIGMA(4)-SIGMA(3))
GO TO 495
474 SIGMAA(I)=SIGMA(6)+(X(I)-G(6))/(G(7)-G(6))*(SIGMA(7)-SIGMA(6))
GO TO 495
476 SIGMAA(I)=SIGMA(7)+(X(I)-G(7))/(G(8)-G(7))*(SIGMA(8)-SIGMA(7))
GO TO 495
478 SIGMAA(I)=SIGMA(8)+(X(I)-G(8))/(G(9)-G(8))*(SIGMA(9)-SIGMA(8))
GO TO 495
480 SIGMAA(I)=SIGMA(4)+(X(I)-G(4))/(G(5)-G(4))*(SIGMA(5)-SIGMA(4))
GO TO 495
490 SIGMAA(I)=SIGMA(5)+(X(I)-G(5))/(G(6)-G(5))*(SIGMA(6)-SIGMA(5))
495 N(I)=N(I)+1
Y(I)=1-EXP(-SIGMAA(I))+Y(I)
500 CONTINUE
510 GO TO 1000
600 ITEN=NN+2
NEND=NN+1
XL(ITEN)=XL(NEND)
G(ITEN)=20.0
SIGMA(ITEN)=SIGMA(NEND)+XL(NEND)*(G(ITEN)-G(NEND))
CDF(ITEN)=1-EXP(-SIGMA(ITEN))
GO TO 405
700 XL(2)=0.0
XL(3)=-(2/(G(3)-G(2)))*ALOG(1-CPF(3))
C=CPF(3)/XL(3)
GO TO 300
800 DO 830 I=2,41
IF (X(I).LT.G(2)) GO TO 810
Y(I)=Y(I)+1.0
GO TO 820
810 Y(I)=X(I)/G(2)+Y(I)
820 N(I)=N(I)+1
830 CONTINUE
PRINT 410
DO 850 I=1,2
PRINT 420,G(I),CPF(I),CPF(I)
850 CONTINUE
GO TO 1000
900 DO 930 I=2,41
IF (X(I).GT.G(2)) GO TO 940
N(I)=N(I)+1
930 CONTINUE
940 PRINT 410
DO 950 I=1,2
PRINT 420,G(I),CPF(I),CPF(I)
950 CONTINUE
1000 CONTINUE
PRINT 1050
1050 FORMAT(///1X,T5,*THE OVERALL CUMULATIVE DISTRIBUTIVE FUNCTION IS:*)
PRINT 1150
1150 FORMAT(//1X,T15,*ACCELERATION-G'S*,T35,*FINAL CDF*)
DO 1300 I=1,41
Y(I)=Y(I)/FLOAT(N(I))
PRINT 1200,X(I),Y(I)
1200 FORMAT(T15,F7.3,T35,F7.3)
1300 CONTINUE
STOP
END
```

INPUT DATA AND COMPONENT CDF FOR CHATTER FAILURE MODE

TEST NO.	SPECTRAL ACCELERATION	C X LAMDA	CDF
1)	0.000	0.000	0.000
	3.350	.500	.500
	5.020	1.000	.823
	6.700	1.000	.956
2)	0.000	0.000	0.000
	3.350	.330	.330
	5.020	.330	.551
	6.700	.830	.778
3)	0.000	0.000	0.000
	3.350	.330	.330
	5.020	.660	.632
	6.700	1.000	.866
4)	0.000	0.000	0.000
	.500	.500	.500
	.750	0.000	.646
	2.000	1.000	.989
	3.000	.500	1.000
	4.000	1.000	1.000
	6.000	1.000	1.000
5)	0.000	0.000	0.000
	.500	.500	.500
	.750	0.000	.646
	2.000	.600	.956
	3.000	.250	.996
	4.000	1.000	1.000
	4.500	0.000	1.000
	6.000	1.000	1.000
6)	0.000	0.000	0.000
	3.320	0.000	0.000
	4.970	.250	.250
	6.630	.500	.685
7)	0.000	0.000	0.000
	4.000	0.000	0.000

INPUT DATA AND COMPONENT CDF FOR CHATTER FAILURE MODE

TEST NO.	SPECTRAL ACCELERATION	C X LAMDA	CDF
8)	0.000	0.000	0.000
	1.650	.330	.330
	3.320	0.000	.553
	4.970	0.000	.553
	6.630	.300	.690
9)	0.000	0.000	0.000
	1.960	1.000	1.000
10)	0.000	0.000	0.000
	.640	1.000	1.000
11)	0.000	0.000	0.000
	.670	.250	.250
	1.340	.067	.479
	2.680	0.000	.554
	5.360	.385	.924
12)	0.000	0.000	0.000
	15.100	.500	.500
13)	0.000	0.000	0.000
	1.660	1.000	1.000
14)	0.000	0.000	0.000
	1.890	0.000	0.000
	4.720	.090	.090
	7.080	0.000	.159
	9.450	.330	.370
15)	0.000	0.000	0.000
	3.320	.330	.330
	4.970	0.000	.451
	6.630	.330	.551
16)	0.000	0.000	0.000
	6.630	0.000	0.000

CALCULATED OVERALL CUMULATIVE DISTRIBUTIVE FUNCTION FOR THE CHATTER FAILURE MODE

THE OVERALL CUMULATIVE DISTRIBUTIVE FUNCTION IS:

ACCELERATION-G'S	FINAL CDF
0.000	0.000
.500	.184
1.000	.304
1.500	.384
2.000	.432
2.500	.456
3.000	.480
3.500	.509
4.000	.541
4.500	.606
5.000	.632
5.500	.669
6.000	.698
6.500	.722
7.000	.799
7.500	.822
8.000	.841
8.500	.856
9.000	.869
9.500	.880
10.000	.891
10.500	.901
11.000	.909
11.500	.916
12.000	.922
12.500	.928
13.000	.933
13.500	.937
14.000	.941
14.500	.944
15.000	.948
15.500	.951
16.000	.954
16.500	.957
17.000	.960
17.500	.963
18.000	.965
18.500	.967
19.000	.969
19.500	.971
20.000	.972

INPUT DATA AND COMPONENT CDF FOR TRIP FAILURE MODE

TEST NO.	SPECTRAL ACCELERATION	C X LAMDA	CDF
1)	0.000	0.000	0.000
	2.000	0.000	0.000
	3.000	.500	.500
	4.000	.250	.823
	4.500	0.000	.851
	6.000	0.000	.851
2)	0.000	0.000	0.000
	6.000	0.000	0.000
3)	0.000	0.000	0.000
	3.320	0.000	0.000
	4.970	.500	.500
	6.630	.400	.857
4)	0.000	0.000	0.000
	7.700	0.000	0.000
5)	0.000	0.000	0.000
	3.000	0.000	0.000
	4.000	.140	.140
6)	0.000	0.000	0.000
	3.350	0.000	0.000
7)	0.000	0.000	0.000
	6.630	0.000	0.000
8)	0.000	0.000	0.000
	5.860	0.000	0.000
	7.840	.077	.077
9)	0.000	0.000	0.000
	2.510	.250	.250
	3.770	.330	.464
	5.020	.125	.587
10)	0.000	0.000	0.000
	.670	0.000	0.000
	1.340	.270	.270
	2.680	0.000	.611
	5.360	.150	.807
	7.540	0.000	.891
	10.050	.540	.990
11)	0.000	0.000	0.000
	6.700	.330	.330

INPUT DATA AND COMPONENT CDF FOR TRIP FAILURE MODE

TEST NO.	SPECTRAL ACCELERATION	C X LAMDA	CDF
12)	SPECTRAL ACCELERATION	C X LAMDA	CDF
	0.000	0.000	0.000
	15.100	.320	.320
13)	SPECTRAL ACCELERATION	C X LAMDA	CDF
	0.000	0.000	0.000
	10.000	0.000	0.000
14)	SPECTRAL ACCELERATION	C X LAMDA	CDF
	0.000	0.000	0.000
	3.320	0.000	0.000
	4.970	.330	.330
	6.630	.910	.853
15)	SPECTRAL ACCELERATION	C X LAMDA	CDF
	0.000	0.000	0.000
	7.080	0.000	0.000
	9.450	.330	.330
16)	SPECTRAL ACCELERATION	C X LAMDA	CDF
	0.000	0.000	0.000
	6.630	0.000	0.000
17)	SPECTRAL ACCELERATION	C X LAMDA	CDF
	0.000	0.000	0.000
	4.970	0.000	0.000
	6.630	.170	.170

CALCULATED OVERALL CUMULATIVE DISTRIBUTIVE
FUNCTION FOR THE TRIP FAILURE MODE

THE OVERALL CUMULATIVE DISTRIBUTIVE FUNCTION IS:

ACCELERATION-G'S	FINAL CDF
0.000	0.000
.500	.006
1.000	.020
1.500	.036
2.000	.049
2.500	.078
3.000	.101
3.500	.142
4.000	.180
4.500	.212
5.000	.239
5.500	.278
6.000	.307
6.500	.353
7.000	.434
7.500	.463
8.000	.532
8.500	.559
9.000	.582
9.500	.603
10.000	.625
10.500	.704
11.000	.723
11.500	.740
12.000	.755
12.500	.768
13.000	.780
13.500	.792
14.000	.802
14.500	.811
15.000	.819
15.500	.828
16.000	.835
16.500	.843
17.000	.849
17.500	.856
18.000	.862
18.500	.867
19.000	.872
19.500	.877
20.000	.882

INPUT DATA AND COMPONENT CDF FOR STRUCTURAL FAILURE MODE

TEST NO.	SPECTRAL ACCELERATION	C X LAMDA	CDF
1)	0.000	0.000	0.000
	6.700	0.000	0.000
2)	0.000	0.000	0.000
	6.700	0.000	0.000
3)	0.000	0.000	0.000
	6.700	0.000	0.000
4)	0.000	0.000	0.000
	6.000	0.000	0.000
5)	0.000	0.000	0.000
	6.000	0.000	0.000
6)	0.000	0.000	0.000
	6.630	0.000	0.000
7)	0.000	0.000	0.000
	11.730	0.000	0.000
	15.640	.500	.500
8)	0.000	0.000	0.000
	5.000	0.000	0.000
9)	0.000	0.000	0.000
	4.000	0.000	0.000
10)	0.000	0.000	0.000
	3.500	0.000	0.000
11)	0.000	0.000	0.000
	24.200	0.000	0.000
12)	0.000	0.000	0.000
	6.630	0.000	0.000
13)	0.000	0.000	0.000
	5.860	0.000	0.000
	7.840	.077	.077

TEST NO.	SPECTRAL ACCELERATION	C X LAMDA	CDF
14)	SPECTRAL ACCELERATION	C X LAMDA	CDF
	0.000	0.000	0.000
	.640	0.000	0.000
	1.290	.090	.090
	1.940	0.000	.172
	2.580	.180	.312
15)	SPECTRAL ACCELERATION	C X LAMDA	CDF
	0.000	0.000	0.000
	5.020	0.000	0.000
16)	SPECTRAL ACCELERATION	C X LAMDA	CDF
	0.000	0.000	0.000
	7.540	0.000	0.000
	10.050	.077	.077
17)	SPECTRAL ACCELERATION	C X LAMDA	CDF
	0.000	0.000	0.000
	6.700	.330	.330
18)	SPECTRAL ACCELERATION	C X LAMDA	CDF
	0.000	0.000	0.000
	15.100	.040	.040
19)	SPECTRAL ACCELERATION	C X LAMDA	CDF
	0.000	0.000	0.000
	10.000	0.000	0.000
20)	SPECTRAL ACCELERATION	C X LAMDA	CDF
	0.000	0.000	0.000
	3.320	0.000	0.000
	4.970	.170	.170
	6.630	.090	.377
21)	SPECTRAL ACCELERATION	C X LAMDA	CDF
	0.000	0.000	0.000
	7.080	0.000	0.000
	9.450	.330	.330
22)	SPECTRAL ACCELERATION	C X LAMDA	CDF
	0.000	0.000	0.000
	6.630	0.000	0.000
23)	SPECTRAL ACCELERATION	C X LAMDA	CDF
	0.000	0.000	0.000
	6.630	0.000	0.000

CALCULATED OVERALL CUMULATIVE DISTRIBUTIVE FUNCTION FOR THE STRUCTURAL FAILURE MODE

THE OVERALL CUMULATIVE DISTRIBUTIVE FUNCTION IS:

ACCELERATION-G'S	FINAL CDF
0.000	0.000
.500	.001
1.000	.005
1.500	.009
2.000	.013
2.500	.019
3.000	.028
3.500	.035
4.000	.045
4.500	.055
5.000	.061
5.500	.074
6.000	.081
6.500	.097
7.000	.177
7.500	.194
8.000	.214
8.500	.233
9.000	.251
9.500	.269
10.000	.289
10.500	.344
11.000	.364
11.500	.382
12.000	.404
12.500	.428
13.000	.450
13.500	.471
14.000	.490
14.500	.507
15.000	.523
15.500	.538
16.000	.555
16.500	.572
17.000	.587
17.500	.600
18.000	.612
18.500	.623
19.000	.632
19.500	.641
20.000	.649