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Load Combination Program Project II Load Combination Methodology Development Interim Report II

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M. W. Schwartz, M. K. Ravindra, J. D. Collins,
J. Hudson, C. A. Cornell, C. K. Chou

Prepared for
U.S. Nuclear Regulatory Commission

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M. W. Schwartz, M. K. Ravindra, J. D. Collins,
J. Hudson, C. A. Cornell, C. K. Chou

Lawrence Livermore Laboratory
7000 East Avenue
Livermore, CA 94550

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ABSTRACT

This second interim report on load combination methodology development has focused on two objectives: methodology development for combining generic dynamic responses, and the application of the load combination methodology to nuclear power plant components. Different component designs have been analyzed in terms of the methodology. Two examples are provided. One is a simple, highly idealized example that illustrates the essential aspects of developing probabilistic design criteria for multiple loadings. The second, more realistic example is a segment of an essential service water line subjected to internal pressure, dead weight, earthquake, an hydraulic transient, and thermal expansion.

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FOREWORD

This is the second interim report on load combination methodology (LCM) development. The first interim report, UCID-18149, was published while Load Combination Methodology constituted Task 3 of the Load Combination Project within the Seismic Safety Margins Research Program (SSMRP). On April 1, 1980, the Load Combination Project at the Lawrence Livermore National Laboratory was officially separated from the SSMRP and has become an independent program. Under this new program, Load Combination Methodology Development is designated Project II (Event Decoupling is Project I) and consists of two tasks. Task 1 is Methodology Development, which seeks to develop a methodology for appropriately combining generic dynamic responses. Both system and component reliability methods are used. Probabilistic methods will be used to determine proper load combinations for mechanical and structural component design to achieve a target reliability. This aspect of the methodology can also be used by the NRC to evaluate component reliability of existing designs. Comparisons can then be made with reliability levels achieved using square root of the sum of the squares (SRSS) and absolute sum (ABS) response combination methods. The system reliability methodology takes into account plant safety and functionability criteria to determine the appropriate target reliabilities for components under various plant conditions. Task 2 deals with the application of the load combination methodology to nuclear power plant components in order to demonstrate its feasibility.

EXECUTIVE SUMMARY

A unified approach is taken to address load combination issues with regard to which loads need to be combined, how they are to be combined, and what ASME service level is applicable. The basis for this approach is probabilistic in that it takes into account the stochastic nature of dynamic loadings and the random variations of structural resistance. The methodology described in this interim report seeks to provide the designer of nuclear power plant components with criteria that will result in designs having a specified level of reliability. Inherent in the methodology is an evaluation procedure that could be used by the NRC in reaching licensing decisions.

This report expands upon the work described in Interim Report I by illustrating in greater detail the steps involved in applying this methodology. Two examples are provided. One is a simple, highly idealized example that illustrates the essential aspects of developing probabilistic design criteria for multiple loadings. We consider an array of pipes of varying lengths and diameters that meet a target limit state probability applicable to the entire ensemble. The loads assumed are dead weight, internal pressure, and a velocity transient. They are considered to be static but have random amplitudes. To simplify the computations, these load magnitudes are assumed to be normally distributed.

The second, more realistic example is a segment of an essential service water (ESW) line subjected to internal pressure, dead weight, earthquake, an hydraulic transient, and thermal expansion. This piping system is characterized by a set of influence coefficients at each of its nodes. These influence coefficients transform the loads at each node to structural responses, and their frequency distributions are developed from existing designs or from a "standard" design generated for this purpose. A set of influence coefficients for a particular design is then obtained by random sampling from these distributions. At each node, for each influence coefficient of a dynamic load, a unit response time history is chosen at random from a collection of time histories stored for a particular range of load magnitudes. The unit response time histories are represented by an upcrossing rate $\nu_u(u)$ and an arbitrary point in time (a.p.t.) probability density function $f_u(u)$. The random sampling of influence coefficients and time histories is repeated as many times as there are nodes in the piping segment.

With the pipe segment defined by the influence coefficients, only the pipe thickness needs to be determined that satisfies the ASME service limits. An initial thickness is obtained by the application of Eq. 3 of ASME 3600. This is checked to see if it satisfies the load combination equations at all the nodes in the pipe. The limit state probability at each node is then obtained by convolving the probability distribution of the resistance with that of the extreme response. The probability of the response is obtained by convolving the probability of the static load effects with the extremes of the combined dynamic load effects using their respective mean upcrossing rate and a.p.t. distributions. In generating the response levels associated with combinations of intermittent loads, all possible load events must be considered. The calculation of the rates of occurrence of different load cases is facilitated by the construction of a load event tree the branches of which represent specific load combination events. Mean occurrence rates for load combinations in which there are initiated loads can be obtained using the load event tree with the branching probabilities that are conditional upon initial loading conditions. The limit state probability is obtained at each node for the extreme value of the response over the life of the component. The limit state probability of the entire component is that associated with the node having the largest limit state probability.

Limit state probabilities may be evaluated for various design criteria involving specific load combinations and assigned service levels. Since this probability would vary with pipe configurations, location within the plant, and geographical location. a number of piping systems designed in accordance with these criteria should be analyzed. A frequency distribution of the implied limit state probability can be obtained and a decision rule for accepting a particular design criterion established based upon a non-exceedance level relative to the target limit state probability.

The Load Combination Methodology may also be used to derive the load and resistance factor values for a set of load combinations having a particular design format. The design format would consist of specified nominal loads, method of analysis (linear, non-linear, etc.), procedures for combining dynamic responses (SRSS, ABS, etc.), and procedures for safety checking the component. The load and resistance factors are treated as variables in the format. These values would be such that an acceptable frequency distribution of the component limit state probability is achieved relative to a target limit state probability.

The choice of a probabilistic approach to load combinations requires that a target limit state probability be established for each component and structural element. This requires an approach that is the reverse of the generally accepted methods of system safety analysis. The limit state probability for the plant must first be established and then be apportioned to the systems, the subsystems and, finally, the components. This allocation at the component level, which can be called the top-down approach, must be such that the required plant limit state probability is not exceeded. The problem with the top-down approach is that there are infinite numbers of combinations of component limit state probabilities that will satisfy the required plant limit state probability. Three approaches to target limit state probability allocation were considered. First is an ideal approach that would take into account the degree of correlation in load intensities between neighboring components, the inclusion of redundant components, and the assumption that component failures are not independent. The problem with this approach is that a great deal of design work must take place before load combinations and detailed design can be considered, since there are two design cycles and one intervening optimization that must be performed before target limit state probabilities can be allocated. Simpler approaches are suggested wherein the specification of expected component loads and resistances from a preliminary design analysis is not required. A procedure is outlined for allocation of limit state probabilities at the system level based upon a plant risk profile related to levels of radioactive release.

1. INTRODUCTION

The NRC requires that structures, systems, and components important to the safety of nuclear power plants be designed to withstand combinations of effects due to natural phenomena, normal operating conditions, and accident conditions. Studies have been conducted to address portions of these load combination issues, but a unified approach has, heretofore, never been undertaken. While load combinations have been incorporated into recent American Concrete Institute (ACI) and American Institute of Steel Construction (AISC) nuclear codes, they have not been completely accepted by the Nuclear Regulatory Commission (NRC). Instead, load combinations have been specified for structures in the Standard Review Plan, but not for mechanical components. Consequently, there is no universally recognized criterion which can serve as a guide to what and how loads should be combined. As a result, the requirement to consider concurrent dynamic events has led to decisions based on judgment, which in turn has led to a situation where safety margins of systems and components may vary widely from plant to plant.

The American Society of Machine Engineers (ASME) Boiler and Pressure Vessel Code, which governs the design of vessels, pumps, piping, steel containment, and component supports, does not specify which loads should be combined. The philosophy of the ASME Code is to place limits on stress which the unfactored load effects must not exceed. These stress limits vary in accordance with the service level assigned to a particular load combination. But the actual load combinations are formulated by the owner through the design specification required by the Code.

The major objective of our load combination research program is to remove the ambiguity that attends the arbitrary selection of load combinations by providing load combination tables which can be associated with particular levels of reliability. The universal application of these load combinations will ensure that levels of reliability for components and systems will be consistent throughout the nuclear industry. It is important to emphasize that the methodology is intended to be in harmony with the philosophy of the ASME Code and that the designer or reviewer need only combine the peak response from individual loads.

In Interim Report I of the Load Combination Project Task 3, the broad outlines of a unified approach to load combination methodology were presented.[1] The present report expands upon the previous work by describing in greater detail the steps involved in applying this methodology. This is done on two levels. One is a simple, highly idealized example which illustrates the essential aspects of the procedure, unencumbered by the more advanced aspects of stochastically combining dynamic responses in a real component. On a higher level, the methodology is applied to an essential service water line in a pressurized water reactor (PWR) plant, subjected to the combined effects of internal pressure, dead weight, seismic loads, thermal loads due to startup/shutdown cycles, and a hydraulic transient.

1.1 BASIS FOR LOAD FACTOR APPROACH

The design format that appears in the ASME Code may be expressed as

$$\phi S_m \geq Y_1 + Y_2 + Y_3 + \ldots , \qquad (1.1)$$

where the Y's are the load effects (in this case stresses), S_m is the stress intensity limit for the material, and ϕ is a factor whose value is governed by the particular service level associated with the component and the nature of the combined loads. While the relationship expressed in Eq. 1.1 is deterministic, we must be aware that the stresses due to the loads and the strength of the material are, in fact, random variables. Computed stresses are based upon load magnitudes that have a low probability of exceedance, while the stress intensity limit represents a material strength having a high probability of exceedance. This is illustrated in Fig. 1.1, which shows the probability density function for both the combined stress and the strength, and the relative location of the values used for design. Note, however, that there is a finite probability that the combined stresses can exceed the factored stress intensity limit. This is represented by the area under the stress distribution curve to the right of ϕS_m. Likewise, there is a finite probability that the strength of the material can be less than the combined stresses, as represented by the area under the strength distribution curve to the left of $Y_1 + Y_2 + Y_3 + \ldots$. Given the actual probability density functions of the stresses and the strength, it is possible to find the

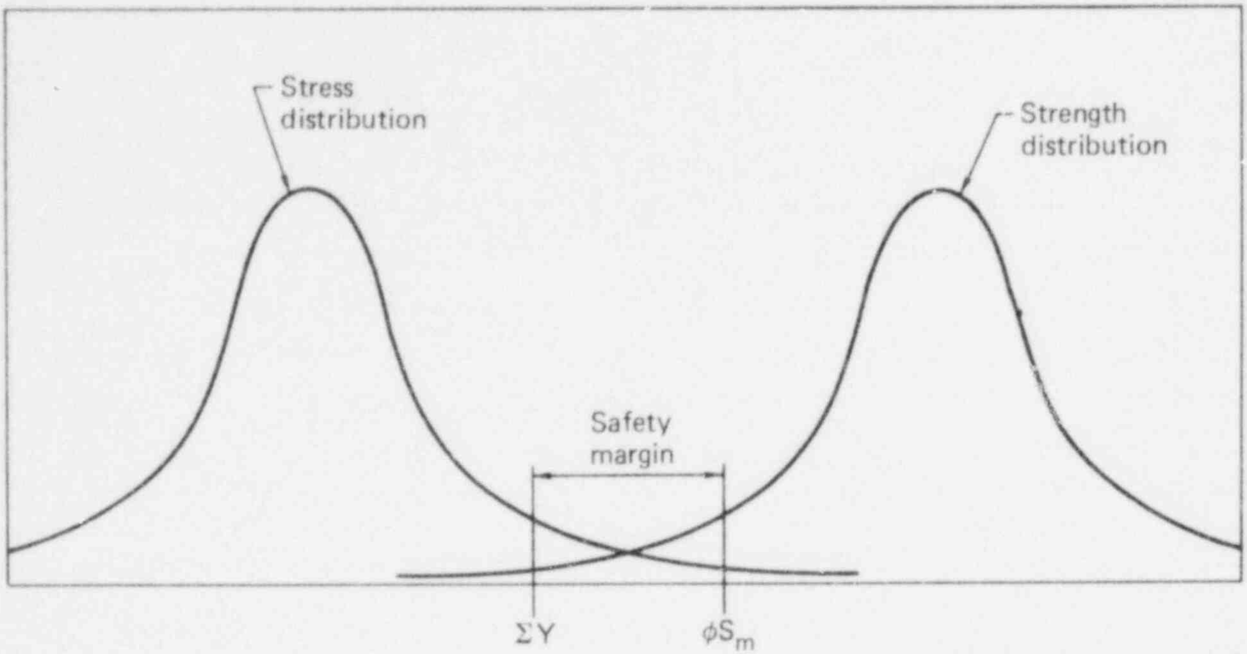


FIG. 1.1. Statistical distributions of stress and strength.

probability that the combined stress exceeds the strength, which is synonymous with the failure probability. Since "failure" may also be associated with loss of function, we prefer the term "limit state probability."

It is also apparent from Fig. 1.1 that if the design stresses are varied, there will be a shift in the stress density function such that the limit state probability will change. This is precisely why arbitrarily selected loads in combination produce a variation in reliability from component to component. On the other hand, if we fix the limit state probability of each component at some acceptably low value, we can, for a specified stress intensity limit, establish a design configuration whose stress levels correspond to the specified limit state probability. This is done with the aid of load factors, each designated by a γ_i. Each set of load factors associated with the load effects corresponds to a specified (or target) limit state probability. Thus, the design format equation takes the form

$$\phi S_m \geq \gamma_1 Y_1 + \gamma_2 Y_2 + \gamma_3 Y_3 + \ldots \tag{1.2}$$

It is not the designer's task to determine the load factors. He simply adjusts his design to satisfy Eq. 1.2, with the assurance that the final product will closely approximate the target limit state probability associated with the load factors. The task of generating the appropriate load factors is carried out by a code-writing group.

1.2 DERIVATION OF LOAD FACTORS--AN EXAMPLE

The method of deriving load factors will now be illustrated by a simple example. What we would like to do is provide a factored load combination equation that can be used to design a simply supported pipe, subjected simultaneously to internal pressure, dead weight, and a velocity transient. The configuration of the pipe is shown in Fig. 1.2.

Since our approach is probabilistic, all the parameters are considered random variables. For some parameters, such as pipe thickness and diameter, the dispersion of their values is small, and we will not consider them as random variables in this example. Only the pressure, dead weight, and initial

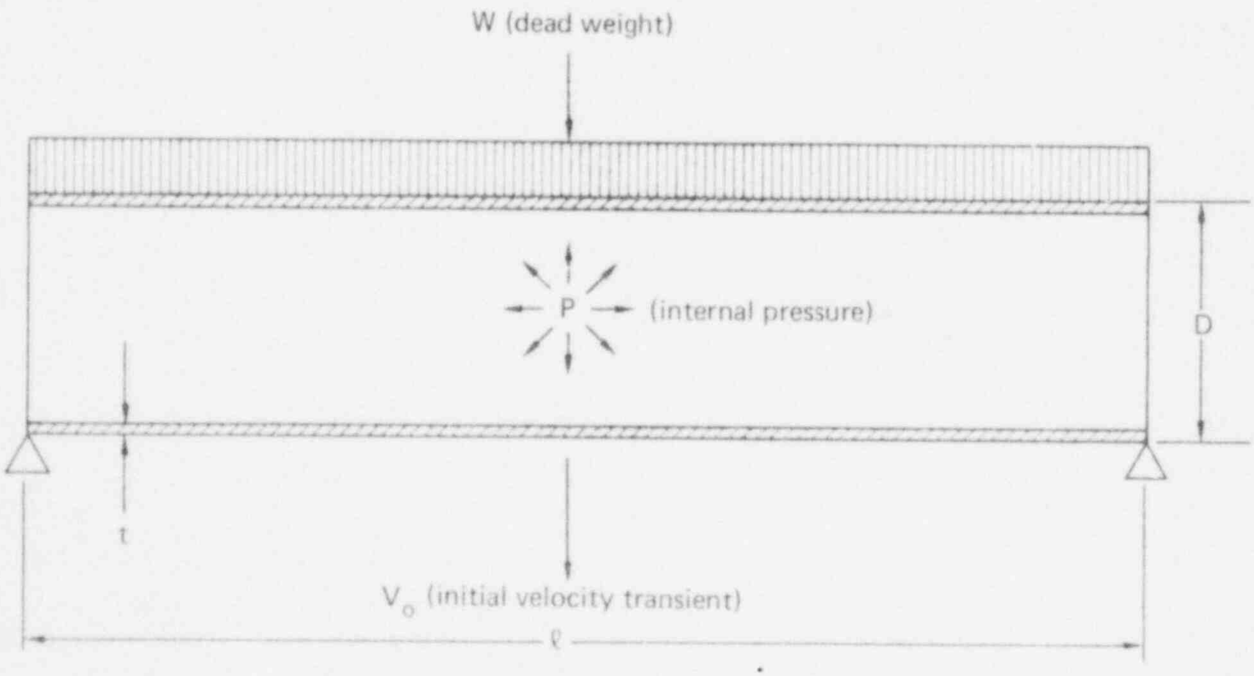


FIG. 1.2. Schematic representation of a simply supported pipe of length ℓ and diameter D.

velocity will be treated as random variables. In addition, we will assume them to be independent and to be normally distributed.

1. We start with the selection of a design format

$$\phi S_m \geq \gamma_1 c_1 V_o + \gamma_2 c_2 \ell + \gamma_3 c_3 p \quad , \tag{1.3}$$

where

V_o = initial velocity transient (in./s),
ℓ = pipe length (in.),
p = internal pressure (lb/in.^{2}),
c_1 = influence coefficient which transforms the initial velocity into a bending stress [(lb/in.^{2})/(in./s)],
c_2 = influence coefficient which transforms the pipe length into a bending stress [(lb/in.^{2})/in.],
c_3 = influence coefficient which transforms the internal pressure into an axial membrane stress [(lb/in.^{2})/(lb/in.^{2})],
S_m = stress intensity limit,
ϕ = resistance factor which reflects the stress categories in the load combination,
$\gamma_1, \gamma_2, \gamma_3$ = load factors which correspond to V_o, ℓ, and p, respectively.

2. We now evaluate the influence coefficients, which take the form

$$c_1 = \frac{4}{\pi}\left[\frac{E}{g}\left(4\Delta_s + \frac{D}{t}\Delta_w\right)\right]^{1/2} \cdot f(\ell)_{max} \quad , \tag{1.4a}$$

$$c_2 = \ell\left(\frac{\Delta_s}{D} + \frac{\Delta_w}{4t}\right) \quad , \tag{1.4b}$$

$$c_3 = \frac{D}{4t} \quad , \tag{1.4c}$$

where

E = modulus of elasticity of pipe material,
g = acceleration due to gravity,

Δ_s = density of pipe material,

Δ_w = density of fluid,

t = pipe thickness,

D = pipe diameter,

$f(\ell)$ = a factor which reflects the influence of all vibration harmonics on the magnitude of the bending moment in the pipe due to the velocity transient.

3. For an assumed set of load factors, we now solve the design format equation for the pipe thickness t that results in a stress equal to the factored code-allowable limit stress. For this calculation the following values were used:

E = 30,000,000 lb/in.^{2},

g = 386 in./s^2,

Δ_s = 0.3 lb/in.^{3},

Δ_w = 0.026 lb/in.^{3},

S_m = 15,600 lb/in.^{2},

ϕ = 1.5 for combined primary membrane and bending stress,

p = 2200 lb/in.^{2},

V_o = 12 in./s.

4. We next assume initial values for load factors, say, $\gamma_1 = \gamma_2 = \gamma_3 = 1$, and determine the thickness of pipe such that Eq. 1.3 is satisfied.

5. Once the thickness of the pipe has been determined, we have a design which can be analyzed probabilistically. The limit state probability is expressed by

$$P_F = 1 - \Phi\left[\frac{\overline{R} - \overline{Y}}{\left(\sigma_R^2 + \sigma_Y^2\right)^{1/2}}\right] , \tag{1.5}$$

where

Φ = Gaussian or normal distribution function for the argument in brackets,

$\bar{R}$ = the mean resistance or strength of the material, corresponding to its assumed failure mode,

σ_R^2 = the variance of the resistance,

$\bar{Y}$ = the mean response,

σ_Y^2 = the variance of the response.

The expressions for $\bar{Y}$ and σ_Y^2 are as follows:

$$\bar{Y} = c_1\bar{V}_o + c_2\bar{\ell} + c_3\bar{p} \tag{1.6}$$

and

$$\sigma_Y^2 = \sum \left(\frac{\partial Y}{\partial X}\right)^2 \sigma^2(X) \tag{1.7}$$

$$= c_1^2\sigma^2(V_o) + c_2^2\sigma^2(\ell) + c_3^2\sigma^2(p) \tag{1.8}$$

The values assumed for determining component limit state probability are

$\bar{R}$ = 30,000 lb/in.^{2} (yield strength),

$\sigma_R = 0.05\bar{R}$ = 1500 lb/in.^{2},

$\sigma(V_o) = 0.10V_o$ = 1.2 in./s,

$\sigma(\ell) = 0.01\ell$,

$\sigma(p)$ = 285 lb/in.^{2}

6. Now we specify a target limit state probability P_T for the pipe component, and note the difference between this probability and the computed limit state probability P_F. Since we want the load factors to represent as broad a class of pipe configurations as possible, we perform the calculation for the combination of eight pipe diameters and five lengths displayed in Table 1.1. Associated with each unique combination of length and diameter is a pipe thickness that limits the stress to the code allowable for the applied load. A limit state probability is also associated with each combination of length and diameter. For this array we set up an objective function,

$$f(\gamma) = \sum_{i=1}^{8} \sum_{j=1}^{5} \left[\frac{\log P_{F_{ij}} - \log P_T}{\log P_T}\right]^2 , \tag{1.9}$$

which we minimize by adjusting the optimum load factors using a quasi-Newton algorithm. The load factors which evolve from this process ensure that a pipe design, using those factors, will have a limit state probability very close to the target value. Consequently, for each specified target limit state probability, there will be a corresponding set of optimized design load factors. These load factors are summarized in Table 1.2 for the entire array of pipe lengths and diameters considered.

TABLE 1.1. Array of pipe diameters and lengths used in the sample calculations of load factors.

LENGTH(IN)	PIPE DIAMETER(IN)							
	10.	12.	14.	16.	18.	20.	22.	24.
120.								
240.								
360.								
480.								
600.								

For a given target limit state probability, an array of 40 pipe thicknesses t_{ij} and an array of 40 limit state probabilities $P_{F_{ij}}$ were generated.

To validate the accuracy of the load factors obtained in this example, we display in Tables 1.3 through 1.9 the actual limit state probabilities and pipe thicknesses that result from using the appropriate set of load factors. We see that, for each combination of pipe length and diameter, the actual limit state probability is close to the specified target. In addition, we see how and to what extent the pipe thicknesses increase as the target limit state decreases.

A measure of the proximity of the limit state probability of each pipe to the target value is revealed in the last four columns of Table 1.2. Column 5 gives the mean values of the limit state probabilities for all 40 pipe components. Columns 6 and 7 give their standard deviations and coefficients of variation, respectively. Column 8 gives the three-standard-deviation non-exceedance probability for each limit state probability, which means that (assuming a normal distribution) there is at least a 99 percent probability that the value in column 8 will not be exceeded.

An important issue yet to be resolved is the choice and number of loads to be combined. To determine the influence of the number of loads in the design format, a case was analyzed which used only the combination of internal

TABLE 1.2. Load factors for the case $\phi S_m = \gamma_1 Y_1 + \gamma_2 Y_2 + \gamma_3 Y_3$.

P_T	γ_1	γ_2	γ_3	$\overline{P}_F$	$\sigma(P_F)$	COV	3σ NEP
10^{-2}	0.875	0.873	1.034	1.003×10^{-2}	6.000×10^{-4}	0.060	1.183×10^{-2}
10^{-3}	0.917	0.913	1.122	1.007×10^{-3}	1.076×10^{-4}	0.107	1.330×10^{-3}
10^{-4}	0.957	0.951	1.197	1.014×10^{-4}	1.632×10^{-5}	0.161	1.504×10^{-4}
10^{-5}	0.995	0.987	1.263	1.023×10^{-5}	2.282×10^{-6}	0.223	1.708×10^{-5}
10^{-6}	1.033	1.023	1.324	1.037×10^{-6}	3.051×10^{-7}	0.294	1.952×10^{-6}
10^{-7}	1.070	1.059	1.381	1.054×10^{-7}	3.970×10^{-8}	0.377	2.245×10^{-7}
10^{-8}	1.108	1.076	1.434	1.076×10^{-8}	5.099×10^{-9}	0.474	2.606×10^{-8}

TABLE 1.3. Computer-generated results for $P_T = 10^{-2}$.

GAMMA1 = 0.8747 GAMMA2 = 0.8733 GAMMA3 = 1.0341

LIMIT STATE PROBABILITIES CORRESPONDING TO 1.0E-02 TARGET LIMIT STATE

LENGTH(IN)	PIPE DIAMETER(IN)							
	10.	12.	14.	16.	18.	20.	22.	24.
120.	1.0179E-02	1.0483E-02	1.0241E-02	1.0596E-02	1.0565E-02	1.0252E-02	1.0267E-02	1.0703E-02
240.	1.0276E-02	1.0452E-02	1.0059E-02	1.0479E-02	1.0154E-02	9.7963E-03	1.0235E-02	1.0413E-02
360.	8.9253E-03	9.9958E-03	1.0114E-02	9.4758E-03	9.5869E-03	9.6197E-03	9.8671E-03	9.9811E-03
480.	9.8264E-03	9.8884E-03	9.2714E-03	9.3955E-03	9.7421E-03	9.9653E-03	9.5402E-03	9.6740E-03
600.	1.2518E-02	1.1013E-02	9.7123E-03	9.6287E-03	9.5777E-03	9.8174E-03	9.4725E-03	9.3105E-03

MEAN = 1.0026E-02 STD.DEV. = 6.0046E-04 C.O.V. = 5.9888E-02

PIPE THICKNESS CORRESPONDING TO 1.0E-02 TARGET LIMIT STATE

LENGTH(IN)	PIPE DIAMETER(IN)							
	10.	12.	14.	16.	18.	20.	22.	24.
120.	3.4554E-01	4.3231E-01	4.7552E-01	5.7677E-01	6.4261E-01	6.2023E-01	7.2422E-01	8.6479E-01
240.	4.2609E-01	5.0137E-01	5.4783E-01	6.4064E-01	6.8411E-01	6.9830E-01	8.2206E-01	9.0794E-01
360.	4.8490E-01	5.9116E-01	6.6253E-01	6.8951E-01	7.5837E-01	8.2166E-01	9.0675E-01	9.6175E-01
480.	6.9108E-01	7.4853E-01	7.7743E-01	8.4327E-01	9.2638E-01	1.0053E+00	1.0363E+00	1.1103E+00
600.	1.1262E+00	1.0649E+00	1.0326E+00	1.0770E+00	1.1279E+00	1.2028E+00	1.2354E+00	1.2800E+00

TABLE 1.4. Computer-generated results for $P_T = 10^{-3}$.

GAMMA1 = 0.9171 GAMMA2 = 0.9134 GAMMA3 = 1.1221

LIMIT STATE PROBABILITIES CORRESPONDING TO 1.0E-03 TARGET LIMIT STATE

LENGTH(IN)	PIPE DIAMETER(IN)							
	10.	12.	14.	16.	18.	20.	22.	24.
120.	1.0301E-03	1.0839E-03	1.0412E-03	1.1044E-03	1.0989E-03	1.0468E-03	1.0467E-03	1.1242E-03
240.	1.0473E-03	1.0787E-03	1.0082E-03	1.0833E-03	1.0250E-03	9.6315E-04	1.0392E-03	1.0712E-03
360.	8.2011E-04	9.9955E-04	1.0197E-03	9.0885E-04	9.2769E-04	9.3270E-04	9.7513E-04	9.9489E-04
480.	9.7481E-04	9.8072E-04	8.7380E-04	8.9830E-04	9.5638E-04	9.9452E-04	9.2083E-04	9.4325E-04
600.	1.4728E-03	1.1867E-03	9.5621E-04	9.4097E-04	9.3140E-04	9.7150E-04	9.1212E-04	8.8439E-04

MEAN = 1.0069E-03 STD.DEV. = 1.0761E-04 C.O.V. = 1.0688E-01

PIPE THICKNESS CORRESPONDING TO 1.0E-03 TARGET LIMIT STATE

LENGTH(IN)	PIPE DIAMETER(IN)							
	10.	12.	14.	16.	18.	20.	22.	24.
120.	3.7949E-01	4.7574E-01	5.2195E-01	6.3483E-01	7.0702E-01	6.7834E-01	7.9402E-01	9.5197E-01
240.	4.7186E-01	5.5490E-01	6.0443E-01	7.0785E-01	7.5403E-01	7.6730E-01	9.0559E-01	1.0009E+00
360.	5.3914E-01	6.5872E-01	7.3693E-01	7.6316E-01	8.3870E-01	9.0777E-01	1.0023E+00	1.0850E+00
480.	7.8508E-01	8.4469E-01	8.7078E-01	9.4206E-01	1.0341E+00	1.1212E+00	1.1516E+00	1.2331E+00
600.	1.3434E+00	1.2360E+00	1.1783E+00	1.2210E+00	1.2727E+00	1.3543E+00	1.3849E+00	1.4307E+00

TABLE 1.5. Computer-generated results for $P_T = 10^{-4}$.

GAMMA1 = 0.9569 GAMMA2 = C.9508 GAMMA3 = 1.1966

LIMIT STATE PROBABILITIES CORRESPONDING TO 1.0E-04 TARGET LIMIT STATE

LENGTH(IN)	PIPE DIAMETER(IN)							
	10.	12.	14.	16.	18.	20.	22.	24.
120.	1.0424E-04	1.1227E-04	1.0594E-04	1.1539E-04	1.1456E-04	1.0719E-04	1.0684E-04	1.1643E-04
240.	1.0681E-04	1.1151E-04	1.0096E-04	1.1218E-04	1.0342E-04	9.4467E-05	1.0554E-04	1.1033E-04
360.	7.4882E-05	9.9961E-05	1.0285E-04	8.6801E-05	8.9422E-05	9.0103E-05	9.6176E-05	9.9037E-05
480.	9.6916E-05	9.7613E-05	8.3034E-05	8.5659E-05	9.3801E-05	9.9262E-05	8.8613E-05	9.1754E-05
600.	1.7504E-04	1.2880E-04	9.4351E-05	9.2060E-05	9.0595E-05	9.6229E-05	8.7700E-05	8.3756E-05

MEAN = 1.0136E-04 STD.DEV. = 1.6316E-05 C.O.V. = 1.6097E-01

PIPE THICKNESS CORRESPONDING TO 1.0E-04 TARGET LIMIT STATE

LENGTH(IN)	PIPE DIAMETER(IN)							
	10.	12.	14.	16.	18.	20.	22.	24.
120.	4.0971E-01	5.1466E-01	5.6317E-01	6.8687E-01	7.6466E-01	7.2923E-01	8.5570E-01	1.0301E+00
240.	5.1388E-01	6.0391E-01	6.5571E-01	7.6901E-01	8.1712E-01	8.2830E-01	9.8079E-01	1.0848E+00
360.	5.8982E-01	7.2210E-01	8.0632E-01	8.3078E-01	9.1222E-01	9.8830E-01	1.0894E+00	1.1791E+00
480.	8.7865E-01	9.3883E-01	9.6002E-01	1.0357E+00	1.1359E+00	1.2303E+00	1.2589E+00	1.3471E+00
600.	1.5882E+00	1.4182E+00	1.3253E+00	1.3638E+00	1.4142E+00	1.5013E+00	1.5282E+00	1.5738E+00

TABLE 1.6. Computer-generated results for $P_T = 10^{-5}$.

GAMMA1 = 0.9953 GAMMA2 = 0.9870 GAMMA3 = 1.2631

LIMIT STATE PROBABILITIES CORRESPONDING TO 1.0E-05 TARGET LIMIT STATE

LENGTH(IN)	PIPE DIAMETER(IN)							
	10.	12.	14.	16.	18.	20.	22.	24.
120.	1.0549E-05	1.1643E-05	1.0784E-05	1.2079E-05	1.1963E-05	1.1000E-05	1.0917E-05	1.2507E-05
240.	1.0898E-05	1.[illegible]40E-05	1.0100E-05	1.1630E-05	1.0410E-05	9.2452E-06	1.0717E-05	1.1373E-05
360.	6.7981E-06	9.9976E-06	1.0378E-05	8.2808E-06	8.5928E-06	8.6775E-06	9.4688E-06	9.8467E-06
480.	9.6566E-06	9.7305E-06	7.8325E-06	8.1525E-06	9.1940E-06	9.9082E-06	8.5068E-06	8.9081E-06
600.	2.0962E-05	1.4062E-05	9.3316E-06	9.0191E-06	8.8169E-06	9.5416E-06	8.4246E-06	7.9149E-06

MEAN = 1.0234E-05 STD.DEV. = 2.2819E-06 C.O.V. = 2.2297E-01

PIPE THICKNESS CORRESPONDING TO 1.0E-05 TARGET LIMIT STATE

LENGTH(IN)	PIPE DIAMETER(IN)							
	10.	12.	14.	16.	18.	20.	22.	24.
120.	4.3791E-01	5.5121E-01	6.0156E-01	7.5576E-01	8.1874E-01	7.7604E-01	9.1291E-01	1.1035E+00
240.	5.5429E-01	6.5092E-01	7.0440E-01	8.2730E-01	8.7880E-01	8.8529E-01	1.0518E+00	1.1641E+00
360.	6.3937E-01	7.8438E-01	8.7408E-01	8.9581E-01	9.8271E-01	1.0613E+00	1.1728E+00	1.2691E+00
480.	9.7616E-01	1.0346E+00	1.0493E+00	1.1286E+00	1.2365E+00	1.3378E+00	1.3636E+00	1.4579E+00
600.	1.8803E+00	1.3155E+00	1.4805E+00	1.5113E+00	1.5588E+00	1.6504E+00	1.6718E+00	1.7159E+00

TABLE 1.7. Computer-generated results for $P_T = 10^{-6}$.

GAMMA1 = 1.0330 GAMMA2 = 1.0228 GAMMA3 = 1.3240

LIMIT STATE PROBABILITIES CORRESPONDING TO 1.0E-06 TARGET LIMIT STATE

LENGTH(IN)	PIPE DIAMETER(IN)							
	10.	12.	14.	16.	18.	20.	22.	24.
120.	1.0875E-06	1.2088E-	1.0981E-06	1.2884E-06	1.2511E-06	1.131[illegible]E-06	1.1164E-06	1.3234E-06
240.	1.1122E-06	1.1954E-06	1.0094E-06	1.2067E-06	1.0513E-06	9.0303E-07	1.0880E-06	1.1730E-06
360.	8.1462E-07	9.9989E-07	1.0472E-06	[illegible]	8.2341E-07	8.3337E-07	9.3069E-07	9.7783E-07
480.	9.6429E-07	9.7145E-07	7.3779E-07	7.7471E-07	9.0067E-07	9.8907E-07	8.1492E-07	8.6337E-07
600.	2.5263E-06	1.5434E-06	9.2518E-07	8.8496E-07	8.5875E-07	9.4712E-07	8.0878E-07	7.4667E-07

MEAN = 1.0367E-06 STD.DEV. = 3.0508E-07 C.O.V. = 2.9426E-01

PIPE THICKNESS CORRESPONDING TO 1.0E-06 TARGET LIMIT STATE

LENGTH(IN)	PIPE DIAMETER(IN)							
	10.	12.	14.	16.	18.	20.	22.	24.
120.	4.6496E-01	5.8649E-01	6.3831E-01	7.8297E-01	8.7088E-01	8.2029E-01	9.6743E-01	1.1744E+00
240.	5.9418E-01	6.9722E-01	7.5190E-01	8.8439E-01	9.3478E-01	9.3999E-01	1.1205E+00	1.2411E+00
360.	8.8913E-01	8.4718E-01	6.4201E-01	9.6005E-01	1.0521E+00	1.1349E+00	1.2547E+00	1.3573E+00
480.	1.0807E+00	1.1354E+00	1.1409E+00	1.2232E+00	1.3387E+00	1.4466E+00	1.4683E+00	1.5686E+00
600.	2.2452E+00	1.6434E+00	1.6492E+00	1.6688E+00	1.7107E+00	1.8061E+00	1.8197E+00	1.8610E+00

TABLE 1.8. Computer-generated results for $P_T = 10^{-7}$.

GAMMA1 = 1.0703   GAMMA2 = 1.0586   GAMMA3 = 1.3809

LIMIT STATE PROBABILITIES CORRESPONDING TO 1.0E-07 TARGET LIMIT STATE

LENGTH(IN)	PIPE DIAMETER(IN)							
	10.	12.	14.	16.	18.	20.	22.	24.
120.	1.0799E-07	1.2561E-07	1.1182E-07	1.3295E-07	1.3101E-07	1.1646E-07	1.1422E-07	1.4030E-07
240.	1.1352E-07	1.2382E-07	1.0079E-07	1.2532E-07	1.0590E-07	8.8010E-08	1.1043E-07	1.2105E-07
360.	5.5341E-08	1.0001E-07	1.0570E-07	7.4131E-08	7.8695E-08	7.9821E-08	9.1334E-08	9.6995E-08
480.	9.6496E-08	9.7131E-08	6.9414E-08	7.3520E-08	8.3198E-08	9.8748E-08	7.7918E-08	8.3548E-08
600.	3.0612E-07	1.7020E-07	9.1936E-08	8.6964E-08	8.37[illegible]0E-08	9.4118E-08	7.7610E-08	7.0332E-08

MEAN = 1.0543E-07   STD = 3.9704E-08   C.O.V. = 3.7658E-01

PIPE THICKNESS CORRESPONDING TO 1.0E-07 TARGET LIMIT STATE

LENGTH(IN)	PIPE DIAMETER(IN)							
	10.	12.	14.	16.	18.	20.	22.	24.
120.	4.9138E-01	6.2114E-01	6.7411E-01	8.2935E-01	9.2204E-01	8.6290E-01	1.0203E+00	1.2441E+00
240.	8.3429E-01	7.4363E-01	7.9905E-01	9.4128E-01	9.9212E-01	9.9345E-01	1.1884E+00	1.3173E+00
360.	7.4004E-01	9.1168E-01	1.0114E+00	1.0247E+00	1.1217E+00	1.2085E+00	1.3365E+00	1.4455E+00
480.	1.1952E+00	1.2435E+00	1.2370E+00	1.3214E+00	1.4443E+00	1.5587E+00	1.5751E+00	1.6811E+00
600.	2.7244E+00	2.1119E+00	1.8368E+00	1.8402E+00	1.87[illegible]6E+00	1.9716E+00	1.9749E+00	2.0118E+00

TABLE 1.9. Computer-generated results for $P_T = 10^{-8}$.

GAMMA1 = 1.1071   GAMMA2 = 1.0949   GAMMA3 = 1.4352

LIMIT STATE PROBABILITIES CORRESPONDING TO 1.0E-08 TARGET LIMIT STATE

LENGTH(IN)	PIPE DIAMETER(IN)							
	10.	12.	14.	16.	18.	20.	22.	24.
120.	1.0907E-08	1.3067E-08	1.1372E-08	1.3984E-08	1.3741E-08	1.1954E-08	1.1667E-08	1.4912E-08
240.	1.1606E-08	1.2877E-08	1.0057E-[illegible]	1.3043E-08	1.0664E-08	8.5395E-09	1.1208E-08	1.2507E-08
360.	4.9577E-09	1.0015E-08	1.0884E-[illegible]	8.9895E-09	7.5001E-09	7.8228E-09	8.9518E-09	9.8153E-09
480.	9.6691E-09	9.7261E-09	6.5202E-09	6.9874E-09	8.6382E-09	9.8697E-09	7.4374E-09	8.0759E-09
600.	3.7218E-08	1.8830E-08	9.1434E-09	6.5513E-09	8.1628E-09	9.3642E-09	7.4432E-09	6.6135E-09

MEAN = 1.0787E-08   STD.DEV. = 5.0757E-09   C.O.V. = 4.7142E-01

PIPE THICKNESS CORRESPONDING TO 1.0E-08 TARGET LIMIT STATE

LENGTH(IN)	PIPE DIAMETER(IN)							
	10.	12.	14.	16.	18.	20.	22.	24.
120.	5.1752E-01	6.5562E-01	7.0948E-01	8.7549E-01	9.7288E-01	9.0452E-01	1.0724E+00	1.3134E+00
240.	6.7511E-01	7.9075E-01	8.4647E-01	9.9667E-01	1.0496E+00	1.0464E+00	1.2563E+00	1.3938E+00
360.	7.9285E-01	9.7885E-01	1.0831E+00	1.0905E+00	1.1924E+00	1.2829E+00	1.4194E+00	1.5347E+00
480.	1.3231E+00	1.3612E+00	1.3390E+00	1.4247E+00	1.5551E+00	1.6759E+00	1.6854E+00	1.7970E+00
600.	3.3924E+00	2.4378E+00	2.0501E+00	2.0302E+00	2.0512E+00	2.1505E+00	2.1403E+00	2.1710E+00

pressure and dead weight to design the pipe for all the loads. This design format can be represented as

$$\phi S_m = \gamma_2{}'c_2\ell + \gamma_3{}'c_3p \quad , \tag{1.10}$$

where $\gamma_2{}'$ and $\gamma_3{}'$ differ from their counterparts in Eq. 1.3. The combined response is still computed using Eq. 1.7. The results of this analysis are summarized in Table 1.10. Note that use of only two loads in the combination results in a wider discrepancy between the mean and target limit state probabilities than does the use of all three loads. In addition, the dispersion about the mean is greater for the two-load case.

Another variation is to use all three loads, as in Eq. 1.3, but to constrain γ_1 and γ_2 to unity. Thus, we have for a design format

$$\phi S_m = c_1V_o + c_2\ell + \gamma_3{}''c_3p \tag{1.11}$$

Table 1.11 summarizes the results for this case. Note that here again the mean deviates to a larger degree from the target than for the case where all three load factors are allowed to vary. It appears that load factors yielding

TABLE 1.10. Load factors for the case $\phi S_m = \gamma_2{}'Y_2 + \gamma_3{}'Y_3$.

P_T	γ_1	γ_2	γ_3	$\overline{P}_F$	$\sigma(P_F)$	COV
10^{-2}	--	1.348	1.442	1.376×10^{-2}	8.792×10^{-3}	0.639
10^{-3}	--	1.438	1.583	1.628×10^{-3}	1.404×10^{-3}	0.862
10^{-4}	--	1.523	1.709	1.958×10^{-4}	2.120×10^{-4}	1.082
10^{-5}	--	1.603	1.826	2.420×10^{-5}	3.144×10^{-5}	1.299
10^{-6}	--	1.694	1.936	2.920×10^{-6}	4.518×10^{-6}	1.547
10^{-7}	--	1.761	2.050	3.700×10^{-7}	6.398×10^{-7}	1.729
10^{-8}	--	1.869	2.147	4.838×10^{-8}	9.833×10^{-8}	2.032

TABLE 1.11. Load factors for the case $\phi S_m = \gamma_1 + \gamma_2 + \gamma_3''\gamma_3$.

P_T	γ_1	γ_2	γ_3	$\overline{P}_F$	$\sigma(P_F)$	COV
10^{-2}	1	1	0.901	1.652×10^{-2}	1.475×10^{-2}	0.893
10^{-3}	1	1	1.032	1.319×10^{-3}	1.087×10^{-3}	0.824
10^{-4}	1	1	1.148	1.070×10^{-4}	6.373×10^{-5}	0.596
10^{-5}	1	1	1.255	9.976×10^{-6}	2.355×10^{-6}	0.236
10^{-6}	1	1	1.359	1.301×10^{-6}	1.104×10^{-6}	0.848
10^{-7}	1	1	1.461	2.866×10^{-7}	6.417×10^{-7}	2.239
10^{-8}	1	1	1.564	1.012×10^{-7}	3.589×10^{-7}	3.547
10^{-9}	1	1	1.668	4.685×10^{-8}	2.073×10^{-7}	4.126
10^{-10}	1	1	1.75	2.470×10^{-8}	1.230×10^{-7}	4.979

limit state probabilities closest to the target may be achieved if all the combined loads are factored.

Some further insights into the role of load factors can be attained if we examine the influence of the statistical parameters upon the values of the load factors. We duplicate the analysis using design format Eq. 1.3, changing only the standard deviation of the initial velocity. These results are summarized in Figs. 1.3 and 1.4, which show the load factors as functions of the target limit state probability for three values of initial velocity standard deviation. It is apparent in Fig. 1.3 that the factor associated with initial velocity increases as the standard devi ion increases. For the load factor associated with the pressure, there is a small decrease, while for the load factor associated with dead weight, there is virtually no change as $\sigma(V_0)$ changes (Fig. 1.4). This is precisely the behavior we should expect, since increasing the dispersion results in lower reliability and requires, in turn, a higher value of the corresponding load factor to achieve the target reliability.

Presented with sets of load factors, the designer is now in a position to determine the thickness of a simply supported pipe of arbitrary length,

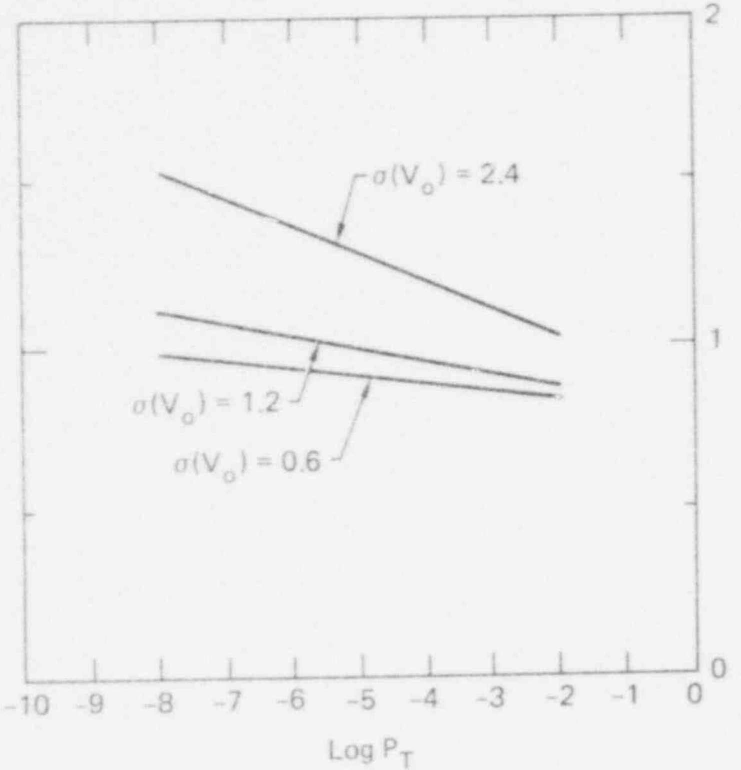


FIG. 1.3. Variation of load factor associated with velocity transient (γ_1) with target limit state probability (P_T) for a range of velocity transient standard deviations.

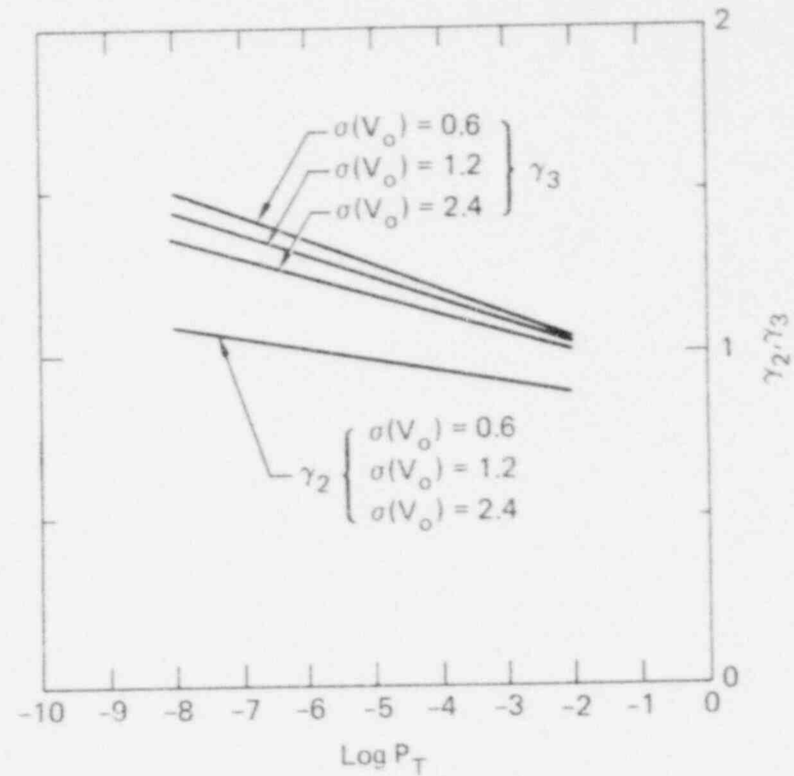


FIG. 1.4. Variation of load factors associated with dead weight (γ_2) and pressure (γ_3) with with target limit state probability (P_T) for a range of velocity transient standard deviations.

diameter, pressure, initial velocity, and material strength for the loading case illustrated that will conform to a specified level of reliability. For a target limit state probability of 10^{-6}, for example, the design equation would be

$$1.5S_m = 1.03c_1V_o + 1.02c_2\ell + 1.32c_3p \quad . \tag{1.12}$$

The values of load and resistance are assumed as follows:

V_o = 13 in./s,
ℓ = 300 in.,
D = 15 in.,
p = 2500 psi,
S_m = 16,500 psi.

The required pipe thickness is 0.776 in. For this thickness, the limit state probability of this design is 4.77×10^{-6}.

1.3 EXTENSION OF THE METHODOLOGY TO MORE COMPLEX CASES

The load and resistance factor design (LRFD) procedure, outlined and illustrated above for a simple, highly idealized component, will now be extrapolated to develop design criteria for real power plant components. The following remarks relate to some of the issues which will be dealt with in the following chapters in connection with these more complex cases of loading and geometry.

In the simple example, the influence coefficients relating load to stress were easily derived. They would not be so for more complex piping configurations. In addition to their more complicated geometry, the responses of complicated piping systems are controlled by numerous restraints (anchors, pipe supports, etc.) and concentrated masses (valves, etc.). The influence coefficients for complex systems are not amenable to closed-form solutions. System and component design and analysis require involved iterative processes. Consequently, analogous to the procedure of selecting influence coefficients over the data space of pipe length and diameter as illustrated in the simple example, a simulation procedure is developed to obtain influence coefficients for the complex piping configuration over the data space of a number of real piping systems.

In our simple example, we considered only three loads, two of which were static. While the velocity transient is an intermittent loading condition, prudence dictates that its maximum response be directly combined with the other two. In more complex cases, there may well be more than one transient loading condition to consider, each having a different time history, duration, and arrival time. Clearly, the assumption that the peak response from each of these loads will occur simultaneously is too conservative. Therefore, in the further development of this study, the realistic random behavior of the loads will be considered in evaluating the component limit state probabilities.

The results presented so far have demonstrated that the averages of the limit state probabilities for the entire array of pipes were close to the target limit state probabilities over a wide range. This means, however, that there is a significant probability that the limit state probability of some designs will exceed the target value. Nonetheless, we can specify load factors in such a way that only an acceptably small fraction of the designs which result from their use have limit state probabilities that exceed the target values. This is an important consideration, especially for the more complex piping systems where the sample space of influence coefficients will exhibit larger dispersions of the random variables than those assumed in our simple example.

Yet to be considered is the task of allocating target limit state probabilities which can be used for deriving and selecting appropriate sets of load factors. Section 4 outlines a systems approach to the problem of assigning target limit state probabilities to nuclear power plant components in a combined loading environment. The assignment procedure considers the dependent nature of failure between components, as well as system-level logical interactions and redundancies. The key to the assignment of target limit state probabilities lies in the assumption of some level of acceptable plant risk. It is gratifying to learn that a new division within the NRC Office of Research has been organized to decide the question of acceptable plant risk.

2. COMPONENT DESIGNS

For practical reasons, the load combinations and load factor values developed for a specified component limit state probability should be applicable for a wide range of design situations. Design situations are characterized by the type of component, the location within the plant, the number and magnitudes of loads acting on the component, the geographic location of the plant, and the type of reactor. Hence, the load factors to be used in these load combinations should be derived by making the component limit state probability approximately equal to the target value over all the design situations. This is achieved by the optimization procedure. However, the procedure requires that for each set of load factor values selected, the components under all the design situations be analyzed and designed.

If we consider the piping subsystem as an example of a component, current design practice is as follows. A piping thickness is first selected from pressure considerations. The support types and locations are chosen such that there is no single point in the piping where the ASME stress limits are exceeded. A satisfactory design of a piping subsystem is achieved after a number of iterations of stress analysis for different arrangements of pipe restraints. This subsystem is then analyzed for the limit state probabilities when subjected to random, time-varying loads. Since several components are to be studied as part of the load combination methodology, this direct procedure of analysis and design requires a large number of costly structural system analyses and piping subsystem analyses. Also, load and resistance factor values in selected load combinations that meet the target limit state probabilities are obtained only after a sufficiently large number of trials, each trial involving the study of component designs as described above. This prohibitively large set of analyses can be avoided by simulating the component designs using the concept of influence coefficients.

2.1 INFLUENCE COEFFICIENT DISTRIBUTION

An influence coefficient gives the effect of a unit load applied at some point in the system on some specific node in the piping subsystem (again, the piping subsystem is an example of a "component"). For instance, if the peak moment response at a node due to a 0.20-g earthquake applied at the foundation level is 500 ft-lb, the moment influence coefficient of the earthquake at the node is (500/0.2) ft-lb/g. It has been found that a more convenient unitless measure for the influence coefficient may be obtained by expressing the coefficient as the ratio of the moment at the node to the average moment over the entire piping subsystem. This is called the influence coefficient ratio.

Let x_d be the design level of load x. For a properly designed piping subsystem, the moments at various nodes i (i = 1, 2, . . . , n) due to x_d are known and are equal to M_{x_i}. The spatial average moment along the piping is denoted M_{x_a}:

$$M_{x_a} = \frac{1}{n}\sum_{i=1}^{n} M_{x_i} \quad . \tag{2.1}$$

The moment influence coefficient ratio at node i is denoted ψ_{x_i}:

$$\psi_{x_i} = \frac{M_{x_i}}{M_{x_a}} \quad . \tag{2.2}$$

If the values of ψ_{x_i} are grouped together in a histogram, a frequency distribution of ψ_x is obtained. Figure 2.1 shows the distribution of moment M_E in a segment of essential service water (ESW) piping nodes due to the operating basis earthquake (OBE) of x_d = 0.009 g. Figure 2.2 is a plot of the histogram and frequency distribution of the moment influence coefficient ratio ψ_E due to the OBE.

In a similar way, the influence coefficient ratio distributions (for moment, acceleration, displacement, etc.) for different loads may be generated.

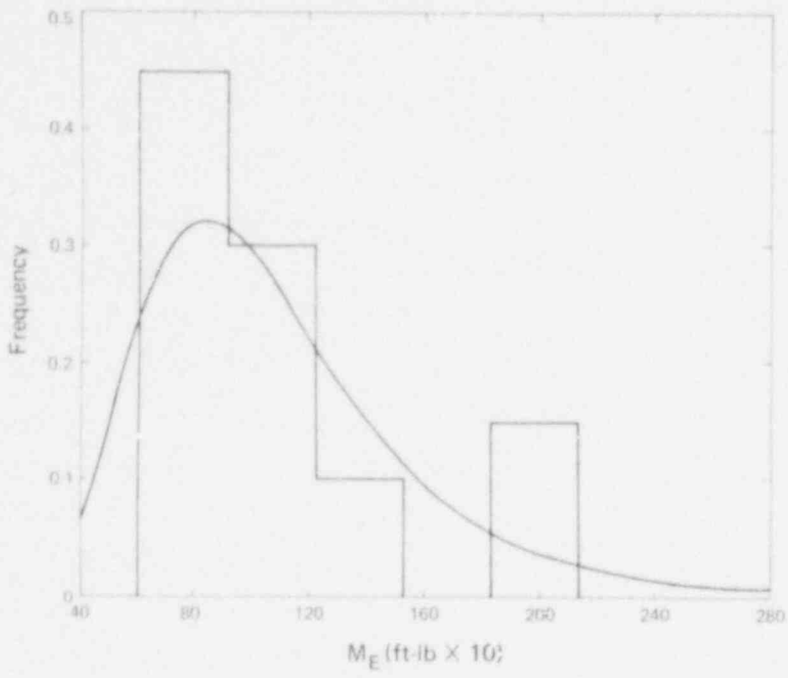


FIG. 2.1. Moment in ESW piping caused by OBE load.

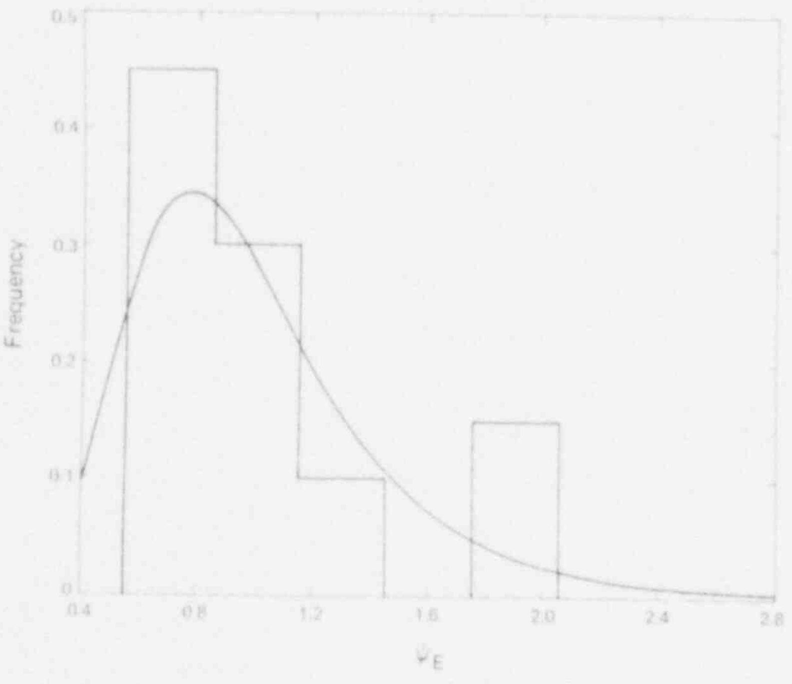


FIG. 2.2. Moment influence coefficient ratio in ESW piping for OBE load.

2.2 GENERATION OF DESIGNS

Different design situations ("components") are handled by simulation in the following way. Assume that there are L different loads acting on the component. The frequency distributions of the response (e.g., moment) influence coefficient ratios for these loads are first developed from an existing design or from a "standard" design generated for this purpose. Obtain a set of influence coefficient ratios ψ_x (x = 1, 2, . . . , L) from these distributions by random sampling. A set of such influence coefficient ratios is associated with each "node" in a fictitious piping subsystem that is properly designed. By the term "properly designed," we mean that the supports are arranged in such a way that the stresses and deformations at all nodes along the piping are within allowable limits. If the piping subsystem consists of about 100 nodes, 100 sets of influence coefficient ratios are to be generated. These sets of influence coefficient ratios characterize our fictitious piping subsystem. Different piping subsystems within a class of components (e.g., ESW line and safety relief valve (SRV) line) may be so characterized using this procedure.

The procedure of generating a design (i.e., layout of the pipe with unknown supports) using the influence coefficient ratios is based on the precept that the frequency distribution of response for a load is the same for different proper designs; although the support locations may differ with designs, the responses at different nodes are only "rearranged" and are represented by the same frequency distribution. This assumption appears to be true for similar components that are subject to the same set of loads. Figures 2.3, 2.4, and 2.5 show the frequency distributions of OBE moments in three SRV lines in a Mark II boiling water reactor (BWR). It can be seen that these frequency distributions are reasonably similar.

With the piping subsystem effectively defined by the influence coefficient ratios, thickness of the piping is the only parameter that is to be decided. A minimum thickness as per Eq. 3 of ASME 3600 is selected. The design is checked to see if it satisfies the load combination equations at all nodes in the piping. If not, an adequate thickness is chosen by iteration. Using this process, a single thickness of the pipe is selected for the entire length. The thickness may also be varied over different segments of the piping.

FIG. 2.3 (top left). Moment influence coefficient ratio in SRV line 1 for OBE load.

FIG. 2.4 (top right). Moment influence coefficient ratio in SRV line 2 for OBE load.

FIG. 2.5 (bottom left). Moment influence coefficient ratio in SRV line 3 for OBE load.

The above procedure of generating a design (called "data point") is based on past design experience. As mentioned earlier, a piping thickness is selected from pressure considerations in current design practice. The support type and locations are then chosen such that there is no single point in the piping where the ASME stress limits are exceeded. In contrast, the selection of a data point represented by the influence coefficient ratios as described herein implies the existence of a well-designed piping subsystem with all the supports specified in the population of such components. This "fictitious" subsystem has yielded the set of influence coefficients. The thickness of pipe needed for this subsystem has to be determined to satisfy the design load combination equations.

In using this procedure for simulating piping subsystem analyses, the following points must be noted:

1. Nodes in a piping subsystem are specified at support locations, at discontinuities (geometric and material), and at locations of in-line equipment (valves, pumps, etc.). In straight runs of piping, nodes are specified at selected intervals such that the critical peak responses are encountered. Although this is a standard industry practice, some differences may exist between designers. A preponderance of noncritical nodes has the effect of lowering the average response (e.g., M_{x_a}). However, this problem is circumvented herein by employing the frequency distributions of influence coefficient ratios derived from either an existing design or a "standard" design. The corresponding average responses are therefore consistently used.

2. The influence coefficient ratio for a response (e.g., moment) has, in general, a bimodal frequency distribution because of the mix of critical and noncritical nodes in the population. The simulation procedure recognizes this bimodality, and the influence coefficient ratios are sampled consistently from such distributions.

3. In a given piping subsystem, the spatial distribution of response (at different nodes) is known. If the response at a node is specified for a particular load, the responses at all other nodes are also obtained. However, the assumption in the proposed simulation procedure is that the response at

any node is a random sample from the response frequency distribution. This frequency distribution is the same for all the nodes for a particular response. Also, the influence coefficient ratios are randomly (independently) sampled. This may raise questions of correlation between nodes. Independent sampling is still admissible, because we do not know the subsystem (i.e., support locations and types); the spatial ordering of nodes is not specified in the simulation procedure. If such spotting of nodes is done, the resulting spatial distribution of response is produced by a fictitious set of pipe supports. While it is true that the nodal responses are deterministic for a given subsystem, it is the lack of knowledge of the support locations (this knowledge may be gained by exorbitant analyses) that makes the nodal responses random; the generation of a multitude of component designs is thereby made feasible.

4. The influence coefficient ratios for a particular response characterizing different nodes in a piping subsystem are sampled independently. As discussed earlier, some correlation between the nodal responses for a specific load exists. This correlation is taken into account approximately in the load combination methodology by considering the limit state probability of a piping subsystem as the maximum over all the nodes (see Eq. 3.30).

5. The frequency distribution of the response influence coefficient ratio is developed using a large number of nodal responses in a piping subsystem (between 100 and 200). For practical reasons, however, we may sample only for 20 nodes. In order to ensure that the entire frequency distribution is represented, a stratified sampling is performed.

2.3 CORRELATION BETWEEN INFLUENCE COEFFICIENTS

The moments at some nodes for different loads may be correlated. For example, if an OBE moment at node 1 is larger than the OBE moment at node 2, it is quite likely that the moment at node 1 due to the safe shutdown earthquake (SSE) is also larger than the SSE moment at node 2. (The effect of structural damping may, however, reverse the situation.) Also, the nodal moments may be negatively correlated; i.e., if the moment at node 1 is less than the moment at node 2 due to thermal loading, the moment at node 1 may be, on the average, greater than the moment at node 2 for OBE loading. Correlation arises from the fact that the geometry and the structural properties (restraints, natural frequencies, damping, etc.) are fixed for the subsystem. This correlation has to be considered in sampling from the frequency distributions of influence coefficient ratios.

Table 2.1 shows an example of the correlation coefficient (ρ) matrix of moment influence coefficient ratios due to different loads. (The correlation coefficient is not a good index of dependence between random variables with skewed probability distributions. Sampling from such variables will be studied in later phases of this project.) The correlation between responses due to some loads is negligible ($|\rho| < 0.2$), whereas between other responses it is very high ($|\rho| > 0.8$). These variables will be considered as statistically independent and dependent, respectively.

Where the absolute value of the correlation coefficient is between 0.2 and 0.8, sampling from such correlated variables is done using the conditional decomposition algorithm proposed by Anderson.[2] It is assumed that the influence coefficient ratios for different loads can be modeled by a multivariate lognormal density function. An equivalent multivariate normal density function is generated by transformation. The algorithm proceeds by decomposing the multivariate normal density into the product of the marginal density of the first variate and the joint density of the remaining variates, conditional upon the value sampled for the first. The joint density is calculated once the first variate has been sampled from its marginal density. The procedure is then applied to the second variate and iterated until values have been assigned to all components of the sample vector.

2.4 RESPONSE TIME HISTORIES

The influence coefficient ratio for a node completely describes the linear response to a static load. Consider a particular kind of load, e.g., thermal. If ψ_{x_i} is the influence coefficient ratio, the moment response at node i due to load level x^j (where j refers to the intensity of the load) is calculated as

$$M_{x_{ij}} = \psi_{x_i} M_{x_a} \left(\frac{x^j}{x_d} \right) , \qquad (2.3)$$

TABLE 2.1. Coefficient of correlation between influence coefficients. A, B, and C are the three local axes for the piping.

		Weight			Thermal			OBE			SSE		
		A	B	C	A	B	C	A	B	C	A	B	C
Wt	A	1.00	-0.05	0.001	-0.500	-0.563	-0.200	0.150	0.175	0.168	0.109	0.095	0.164
	B		1.00	0.225	-0.003	-0.194	0.137	-0.235	-0.343	0.035	-0.260	-0.360	0.041
	C			1.00	-0.277	-0.017	0.270	-0.424	-0.135	0.121	-0.414	-0.167	0.179
Th	A				1.00	0.044	-0.354	0.320	0.134	-0.400	0.331	0.241	-0.412
	B					1.00	0.018	0.040	0.137	-0.298	0.086	0.200	-0.289
	C						1.00	-0.320	0.020	0.527	-0.210	-0.016	0.534
OBE	A							1.00	0.391	0	0.996	0.416	-0.037
	B								1.00	0.519	0.369	0.992	0.511
	C									1.00	-0.035	0.443	0.998
SSE	A										1.00	0.397	-0.071
	B											1.00	0.433
	C												1.00

where M_{x_a} is the average moment due to the design load x_d (Eq. 2.1). If the response is nonlinear,

$$M_{x_{ij}} = \psi_{x_i} M_{x_a} k_j\left(\frac{x^j}{x_d}\right), \tag{2.4}$$

where k_j is a multiplier to reflect the nonlinearity in response. For a dynamic load, the peak amplitude does not completely describe the response at a node. A set of response time histories will, in general, be needed to represent the random dynamic response at a node.

As an example, assume that the response time histories have been developed at n nodes (a representative piping subsystem has between 100 and 200 nodes) for six different real earthquake time histories scaled to a single value of peak ground acceleration. Each response time history is normalized by dividing the amplitude at any instant by the peak absolute amplitude (e.g., $M_{x_{ij}}$) in that response time history. These unit (normalized) response time histories are stored in the form of the mean upcrossing rate function $\nu_u(r)$, and the arbitrary-point-in-time (a.p.t.) probability density function $f_u(r)$. The mean upcrossing rate is the expected number of crossings per unit time of the response process from a stress level less than r to a stress level greater than r. The a.p.t. probability density function describes the distribution of response levels viewed at an arbitrary point in the response process. Figures 2.6, 2.7, and 2.8 show a typical response time history, the mean upcrossing rate function, and the a.p.t. probability density function, respectively. For any selected node with influence coefficient ratio ψ_{x_i}, the upcrossing rate of moment response $\nu_M(m)$ is given by

$$\nu_M(m) = \nu_u\left(\frac{m}{M_{x_{ij}}}\right) , \tag{2.5}$$

where m is the response level and $M_{x_{ij}}$ is given by Eq. 2.3 or 2.4. The a.p.t. probability density function of moment response is obtained as

$$f_M(m) = \frac{1}{M_{x_{ij}}} f_u\left(\frac{m}{M_{x_{ij}}}\right) \tag{2.6}$$

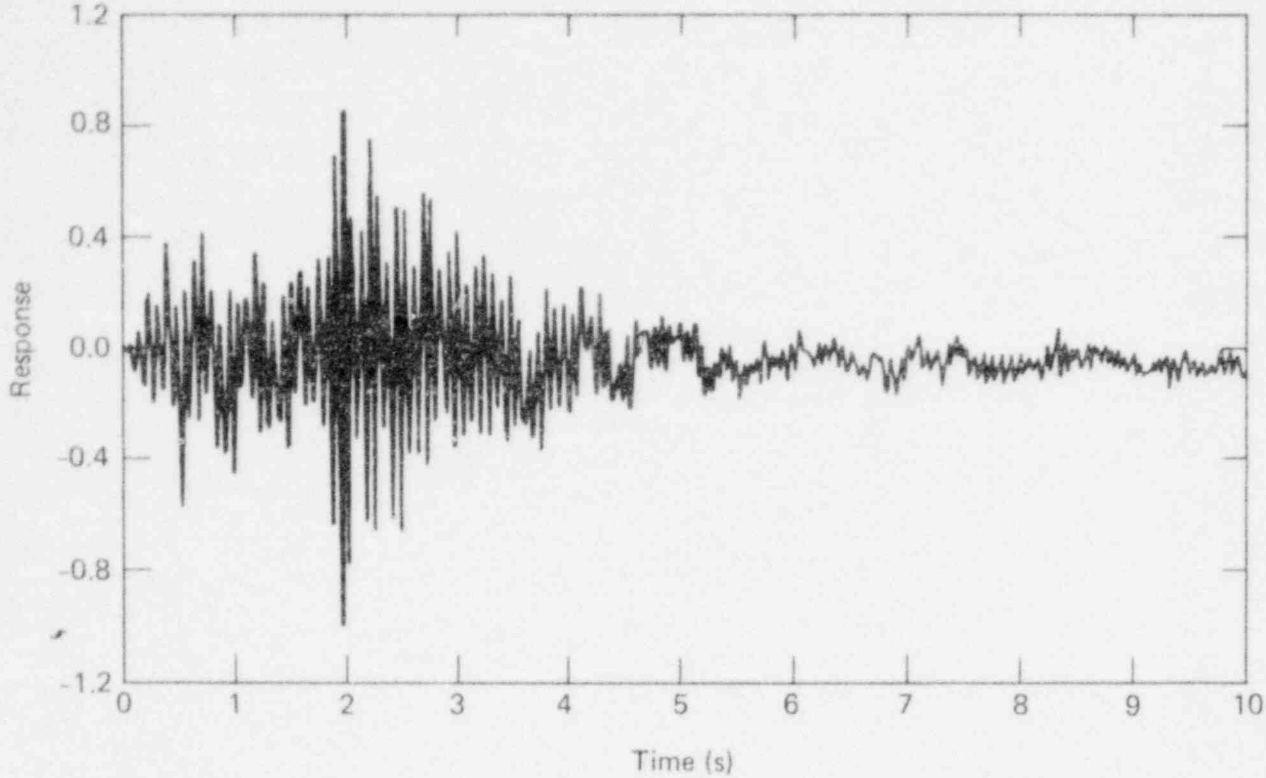


FIG. 2.6. Typical response time history.

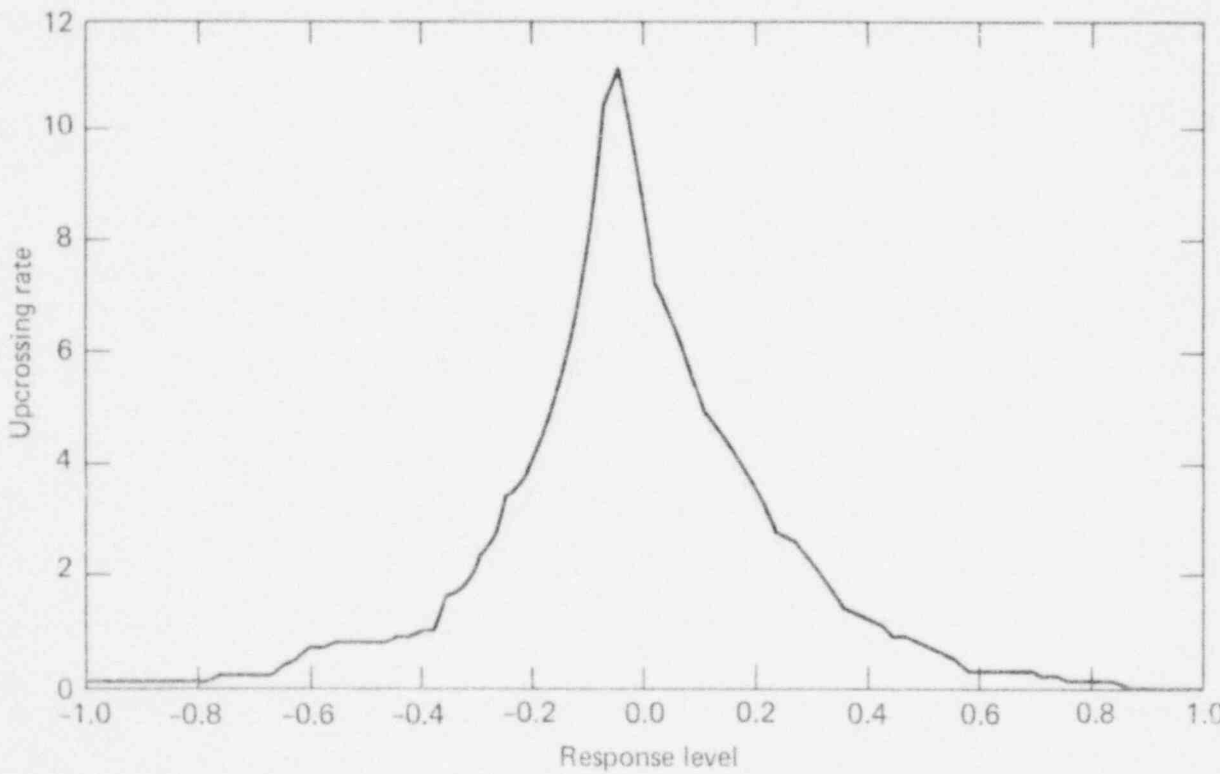


FIG. 2.7. Mean upcrossing rate function for the time history above.

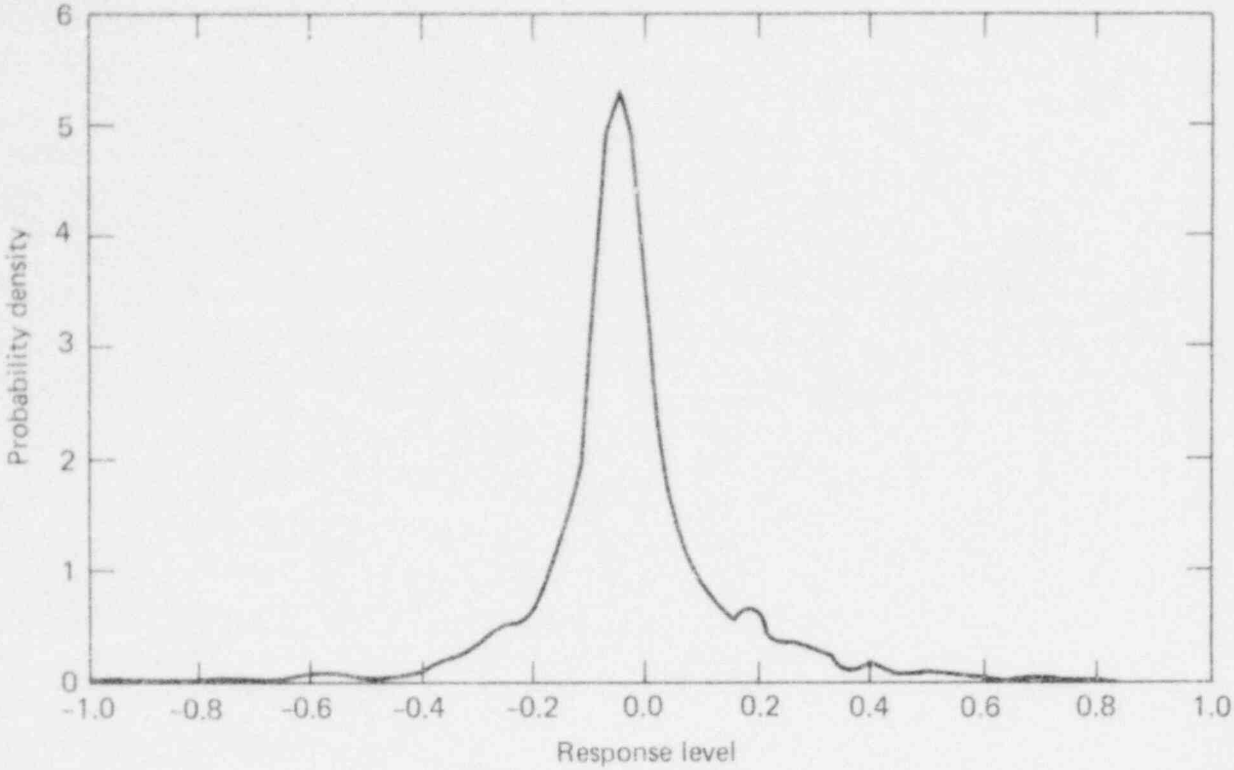


FIG. 2.8. Arbitrary-point-in-time probability density function for the time history in Fig. 2.6.

2.5 SAMPLING

As described earlier, a set of influence coefficient ratios corresponding to different types of loads acting on the component characterizes a node. A set of n such nodes represents a fictitious component. Sampling for a node involves a random selection of a set of influence coefficient ratios from their frequency distributions. The uncorrelated ($|\rho| < 0.2$) influence coefficient ratios are sampled using the appropriate frequency distributions fitted to the data. For correlated influence coefficient ratios, their frequency distribution is assumed to be jointly normal or lognormal, and the sampling is done using the conditional decomposition algorithm described earlier.

At each node, for each influence coefficient ratio of a dynamic load, a unit response time history is chosen at random from the collection of time histories stored for that particular range of load intensities. As an example, for an earthquake load with a peak ground acceleration of 0.10 g, the unit response time history, represented by $\nu_u(u)$ and $f_u(u)$ corresponding to one out of a set of six different real earthquake base motions and low damping, is selected at random. The values of ν and f are obtained for the particular node in the component using Eqs. 2.5 and 2.6

Such random sampling of influence coefficient ratios and time histories is repeated n times (in a typical case n is about 110; for illustration, n is taken as 20) to generate a single sample design of a subsystem ("component"). For each component type, a sample of r different design will be studied. (Initially, we have a set of 20.)

The frequency distributions of influence coefficient ratios and the collection of unit response time histories used may be influenced by the type and class of component. For example, if the derived load factor values are to be applicable for a component type at different locations within the plant, the frequency distributions of influence coefficient ratios should be developed to reflect the effect of the various locations. For practical reasons, it may become necessary to have a single set of load combinations applicable to different components (e.g., all Class I piping). In deriving such a set of load factor values, it is important to assign "weights" to different components according to their relative frequency of occurrence within the plant, and perhaps based on their importance.

3. METHODOLOGY

The load combination methodology development has two objectives:

- To provide a procedure to evaluate the reliability implied by a set of design criteria. This will be useful to the NRC in its licensing review.
- To derive appropriate load and resistance factor values in load combinations for the design of nuclear components to meet a target limit state probability.

Evaluation of design criteria is achieved by designing several components and assessing their limit state probabilities. A criterion is needed to judge whether these limit state probabilities are acceptable. Development of design load combinations requires, in addition, the selection of a design format and optimization.

3.1 RELIABILITY EVALUATION

The procedure for evaluating the limit state probability implied by a design is described by the following illustration.

The criteria used for the design of a typical ESW line (Class II piping) between the auxiliary building and the containment in a PWR are shown in Table 3.1. This segment of the ESW line is 16 inches in diameter and is anchored at the auxiliary building floor and at the containment. It has 20 nodes and 6 rigid restraints (Fig. 3.1). There is a butterfly valve attached to the pipe. The limit states to be considered are rupture of the pipe and rupture or buckling of a restraint. The butterfly valve has limitations on the accelerations in the A, B, and C local directions. Exceedance of these limits, listed in Table 3.2, constitutes an additional limit state.

TABLE 3.1. Design criteria for a typical ESW line between auxiliary building and containment in a PWR.

Load combination[a]	Service level[b]
P + W	sustained loads (design)
P + W + OBE	B
P + W + SSE	C
P + W + HYDTR	B
TRNG	A/B
P + W + OBE + HYDTR	C

[a]Abbreviations: P, design pressure; W, weight; OBE, operating basis earthquake load; SSE = safe shutdown earthquake load; S_h, basic material allowable stress; HYDTR, hydraulic transient load; TRNG, thermal range.

[b]Allowable stresses: sustained loads, S_h = 15,000 psi; service level B, $1.2S_h$ = 18,000 psi; service level C, $1.8S_h$ = 27,000 psi; thermal expansion range, S_A = 22,500 psi.

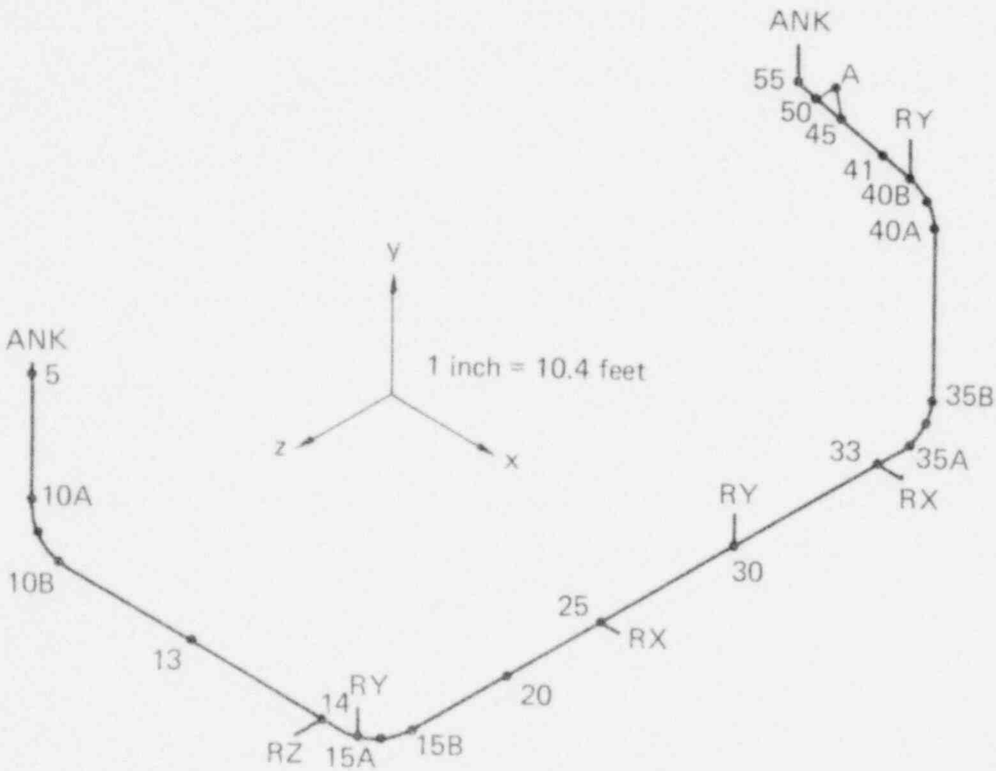


FIG. 3.1. Model of ESW piping line.

TABLE 3.2. Acceleration limitations on the ESW butterfly valve.

Direction	Limiting Acceleration, g	
	Service level B	Service level C
A	2.25	3.00
B	2.25	2.50
C	2.50	3.00

3.1.1 Influence Coefficient Ratios and Response Time Histories

As a first step towards generating different designs in order to evaluate the design criteria, the frequency distributions of influence coefficient ratios of responses for different loads will have to be developed. This can be done by performing a "standard" design or by extracting the required information from an existing design. The latter approach is pursued herein. The moment influence coefficient ratio distributions for weight (moments in local axes A, B, and C), OBE (M_A, M_B, and M_C), SSE (M_A, M_B, and M_C), and HYDTR M_A, M_B, and M_C); and the influence coefficient ratio distributions for forces at rigid supports and for the accelerations at a valve in the three directions are developed as described earlier.

This segment of the ESW piping is supported at three floor levels in the auxiliary building and at one level in the containment building. From the analysis of the structural system, the support motions corresponding to OBE and SSE are obtained. The response time histories at nodes in the piping produced by the multiple support excitations are recorded. The response time histories are normalized, reduced to ν and f functions, and stored for later sampling. Similarly, the response time histories due to hydraulic transients are generated, normalized, reduced, and stored.

3.1.2 Simulation of Component Designs

A node in the piping is represented by a set of influence coefficient ratios. The influence coefficient ratios are randomly sampled from the five frequency distributions for responses, one each for weight, thermal, hydraulic transient, OBE, and SSE loads. The correlations between the influence coefficient ratios of the different loads are included in this simulation.

The design thickness of the piping is determined in the following way. A sample set of 20 nodes is selected to form a sample of the "fictitious" ESW line. A minimum thickness t_m of the piping is selected using ASME Section NC-3651.1:

$$t_m = \frac{PD_o}{2(S + Py)} + A \quad , \tag{3.1}$$

where

P = internal design pressure (psi),

D_o = outside diameter of pipe (in.),

S = maximum allowable stress for material at design temperature (psi),

y = 0.4, for $D_o/t_m > 6$,

$= \dfrac{D_o - 2t_m}{2(D_o - t_m)}$, for $D_o/t_m \leq 6$,

A = an additional thickness to allow for material removed in threading or counterboring, for corrosion or erosion, for material manufacturing tolerances, and for bending (in.). The values of A are tabulated in ASME Code Table NC-3641.1(a)-1.

At each node the following equations are checked:

$$\frac{PD_o}{4t_n} + \frac{0.75iM_A}{Z} \leq 1.0S_h \quad , \tag{3.2}$$

$$\frac{P_{max}D_o}{4t_n} + 0.75i\left(\frac{M_A + M_B}{Z}\right) \leq 1.2S_h \quad \text{(for service level B)} \quad , \tag{3.3}$$

$$\frac{P_{max}D_o}{4t_n} + 0.75i\left(\frac{M_A + M_B'}{Z}\right) \leq 1.8S_h \quad \text{(for service level C)} \quad , \tag{3.4}$$

$$\frac{iM_C}{Z} \leq S_A \quad \text{(for thermal expansion range)} \quad , \tag{3.5}$$

where

i = stress intensification factor,
P = internal design pressure,
P_{max} = peak pressure,
M_A = resultant moment loading on cross section due to weight,
M_B = resultant moment on cross section due to loads specified for service level B in load combinations 2 and 4, exclusive of weight (Sec. 3.1),
M_B' = resultant moment on cross section due to loads specified for service level C, i.e., load combination 3, exclusive of weight (Sec. 3.1),
M_C = range of resultant moments due to thermal expansion,
t_n = nominal wall thickness,
Z = section modulus.

Note that the responses due to dynamic loads are combined using the square root of the sum of the squares (SRSS) procedure.

For the first trial, the value of t_n is equal to t_m. If the above equations are satisfied for all nodes, the design of the piping subsystem is deemed complete. If not, a larger thickness is selected to satisfy Eqs. 3.2 through 3.5. This piping subsystem with known wall thickness and distribution of responses will be analyzed later to determine the implied limit state probability values.

Using a similar procedure, six rigid supports are simulated--i.e., the reactions at these supports due to different loads are sampled from the influence coefficient ratio frequency distributions. The supports are selected from Table 3.3 corresponding to the maximum total load for load combinations of each service level. Anchors are treated as two nodes in the piping with different stress intensification factors.

TABLE 3.3. Maximum load capacities (in pounds) for struts and rigid restraints.

Support size no.	Levels A and B (upset)	Level C (emergency)	Level D (faulted)
A	650	870	1,200
B	1,500	2,250	3,000
C	4,500	6,000	6,000
1	8,000	9,600	10,320
2	11,630	13,960	15,000
3	15,700	18,840	20,250
4	20,700	24,840	26,700
5	27,200	32,640	35,081
6	33,500	40,200	43,220
7	58,734	78,312	86,500
8	110,000	132,000	165,000

3.1.3 Limit State Probability Calculation

The piping subsystem that is designed for a given set of load combinations is subjected to stochastic load processes and has uncertainties inherent in the piping material, analysis, and fabrication. Any evaluation of the probability P_F of the component reaching a limit state (e.g., rupture) should explicitly consider these aspects of uncertainty.

The method of evaluating P_F is based on the probability distribution of resistance R of the component and of extreme (combined) load effect (response) on the component. The probability distribution of the load effect is developed from convolving probability distributions of static load effects and the extreme of the combined time-varying "static" and/or dynamic load effects. The latter distribution is approximated by a method which makes use of the mean upcrossing rate $\nu_Y(y)$ as a function of the response y, and the a.p.t. distribution of response, as described by the probability density function $f_Y(y)$.

For the purposes of calculating the probability distribution of the combined response, three types of loads are identified: static, continuous, and intermittent. An example of a static load is the dead load due to self-weight. Loads due to normal operating pressure and temperature are examples of continuous loads. Earthquake and operating incidents are some examples of intermittent loads. Figure 3.2 shows the response time histories of these load types.

Static Loads. Static loads can be treated as random variables characterized by probability density functions. If two static load effects c_1X_1 and c_2X_2 are experienced by a component (where c_1 and c_2 are the influence coefficients and X_1 and X_2 are the imposed loads), the combined response $Y_s = (c_1X_1 + c_2X_2)$ is expressed by its probability density function $f_{Y_s}(y)$:

$$f_{Y_s}(y) = \frac{1}{c_1c_2} \int_{-\infty}^{\infty} f_{X_1}\left(\frac{y - u}{c_1}\right) f_{X_2}\left(\frac{u}{c_2}\right) du \quad . \tag{3.6}$$

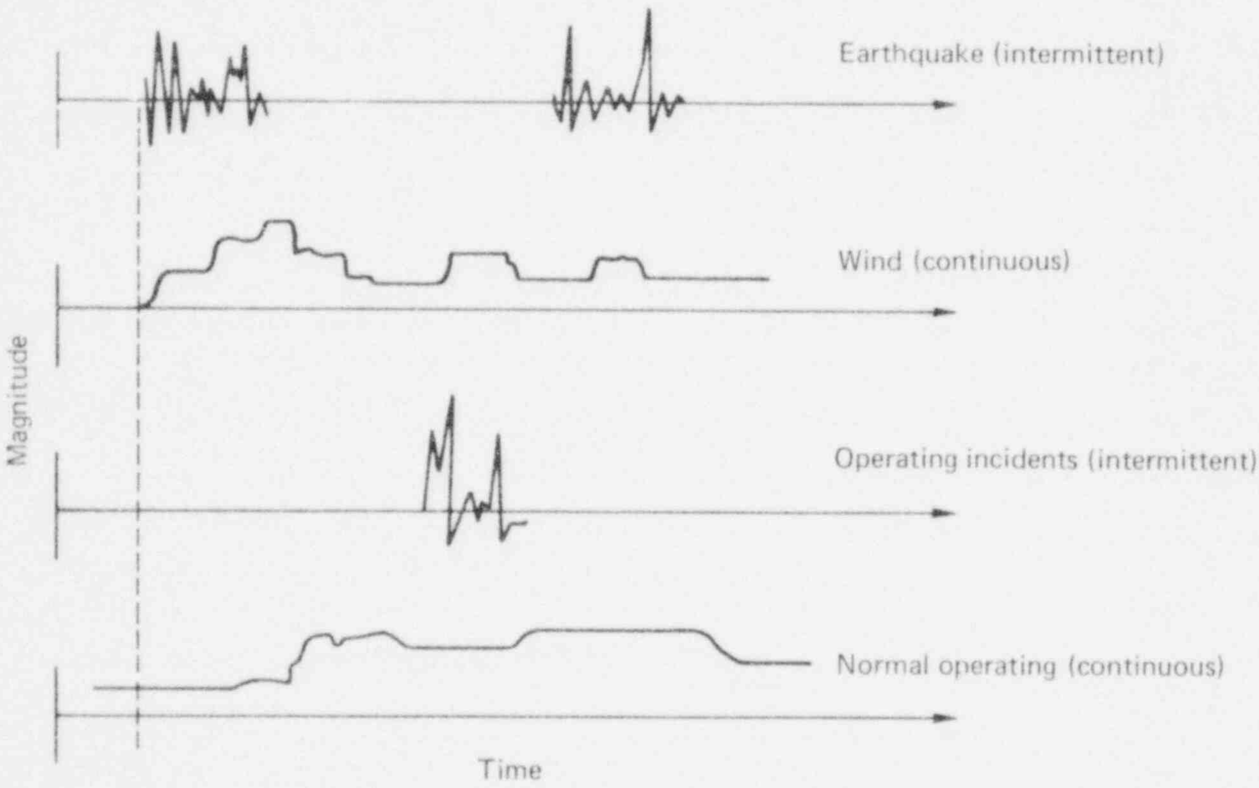


FIG. 3.2. Schematic time histories of typical initial loads.

Continuous Loads/Stationary Response. The procedure for calculating the upcrossing rate $\nu_{Y_c}(y)$ and the a.p.t. probability density function $f_{Y_c}(y)$ of the combined reponse Y_c is described below. Since the continuous load processes are "always on," they will certainly coincide. Therefore, the combined response $Y(t)$ is the sum of the individual responses $c_i X_i(t)$:

$$Y_c(t) = \sum_{\text{all } i} c_i X_i(t) \quad . \tag{3.7}$$

Let Y_c be the combination of two responses c_1X_1 and c_2X_2; $\nu_1(x)$ and $\nu_2(x)$ are the mean upcrossing rate functions of the two load processes $X_1(t)$ and $X_2(t)$. $f_1(x)$ and $f_2(x)$ are the a.p.t. probability density functions of the load processes.

At the specific node k in the component, c_1 and c_2 are the influence coefficients of loads 1 and 2. The mean upcrossing rate $\nu_{Y_1}(y_1)$ of load effect $Y_1 = c_1X_1(t)$ is

$$\nu_{Y_1}(y_1) = \nu_1(y_1/c_1) \quad . \tag{3.8}$$

The a.p.t. probability density function $f_{Y_1}(Y_1)$ of the load effect $Y_1 = c_1X_1(t)$ is

$$f_{Y_1} = \frac{1}{c_1} f_1(y_1/c_1) \quad . \tag{3.9}$$

Similar results hold for the load effect $Y_2 = c_2X_2(t)$.

The mean upcrossing rate of the combined load effect $Y_c(t)$ $= c_1X_1(t) + c_2X_2(t)$ is

$$\begin{aligned} \nu_{Y_c}(y) &= \int_{-\infty}^{\infty} \nu_{Y_1}(u)\, f_{Y_2}(y-u)du + \int_{-\infty}^{\infty} \nu_{Y_2}(u)\, f_{Y_1}(y-u)du \\ &= \nu_{Y_1}{*}f_{Y_2} + \nu_{Y_2}{*}f_{Y_1} \quad , \end{aligned} \tag{3.10}$$

where the asterisk denotes convolution. The probability density function of $Y_c(t)$ is expressed as

$$f_{Y_c}(y) = f_{Y_1} * f_{Y_2} \tag{3.11}$$

Generalizing for the case of n responses, we obtain

$$Y_c(t) = \sum_{i=1}^{n} Y_i(t) \tag{3.12}$$

and

$$\begin{aligned} \nu_{Y_c} &= \nu_{Y_1} * f_{Y_2+Y_3+\ldots+Y_n} + \nu_{Y_2} * f_{Y_1+Y_3+\ldots+Y_n} \\ &\quad + \ldots + \nu_{Y_n} * f_{Y_1+Y_2+\ldots+Y_{n-1}} , \end{aligned} \tag{3.13}$$

where

$$f_{Y_1+Y_2+\ldots+Y_{n-1}} = f_{Y_1} * f_{Y_2} * f_{Y_3} * \ldots * f_{Y_{n-1}} . \tag{3.14}$$

The probability density function of $Y_c(t)$ is then

$$f_{Y_c} = f_{Y_1} * f_{Y_2} * f_{Y_3} * \ldots * f_{Y_n} . \tag{3.15}$$

Intermittent Loads/Quasi-Stationary Responses. In analyzing the response levels associated with combinations of intermittent loads, all possible load events must be considered, e.g., load 1 alone, load 2 alone, and loads 1 and 2 coinciding. The procedure for calculating the rate of occurrence of a load case q (q = 1, 2, . . . , Q), the mean upcrossing rate $\nu_q(x)$, and the probability distribution $f_q(x)$ of the response given below is described in detail by Winterstein.[3]

Since we are interested in the combined response due to intermittent loads, two additional parameters are required to describe the individual load process: λ_i is the mean rate of occurrence of load events of type i, and T_i is the duration of load events of type i. In this study, T_i is taken to be the mean duration (μ_i) of the event.

The calculation of the rates of occurrence of different load cases is facilitated by the construction of a load event tree. For this purpose, two classes of loads are identified:

- Initial loads: loads which have a potential of initiating additional loads on the component due to failures of other parts of a system. This class of loads includes loads due to earthquake, wind, hurricane, normal operation and operating incidents, SRV discharge, etc. Some examples of the time histories of responses to initial loads were given in Fig. 3.2.
- Initiated loads: loads on a component due to the response and/or failure of another part of a system as a consequence of some initial load. Loads in this class arise from pipe breaks, valves failing to close, turbine trips, etc. An example of the relationship between the time history of the response to the initial load--e.g., due to an earthquake--and the response to an initiated load--e.g., a pipe break--is given in Fig. 3.3.

The branches of a load tree give the specific load combination events. A load tree is constructed as follows. Each initial load is divided into a set of discrete levels. At each level of initial load, e.g., earthquake peak acceleration of 0.20 g, any level of a second, simultaneous initial (noninitiated, random) load could act on the component--e.g., a hydraulic transient load. The combined effect of these two initial loads may trigger a

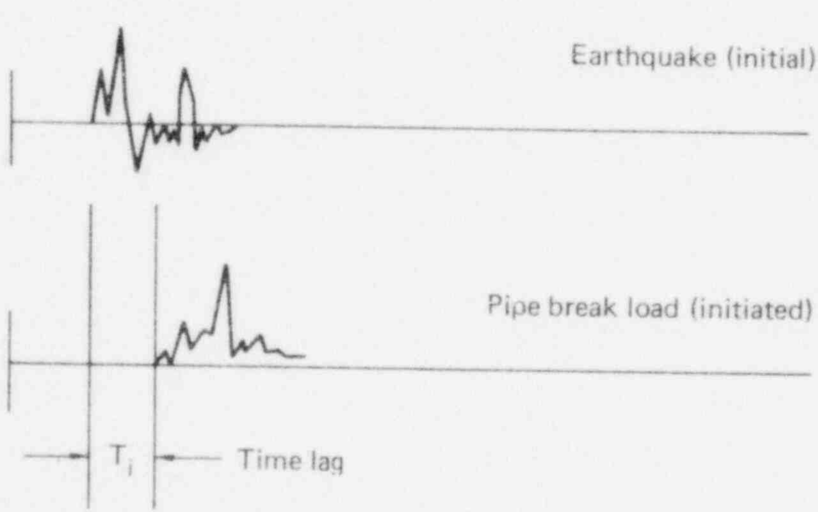


FIG. 3.3. Schematic representation of the relationship between the time histories of typical initial and initiated loads.

pipe break; the size of the break and the magnitude of the resulting (initiated) load depends on the combined effect of initial loads.

Mean occurrence rates for load combinations in which there are initiated loads can be obtained using the load event tree with the branching probabilities that are conditional on the present loading conditions--e.g., hydraulic transient and earthquake; or pipe break, earthquake, and SRV. The complete question of dependent load processes will be addressed in a later report. In the illustration here, we ignore hydraulic transients and pipe breaks caused by an earthquake.

In the case of two initial loads, the mean rate of occurrence of the coincident events is given by

$$\lambda_{1+2} = \lambda_1 \lambda_2 (\mu_1 + \mu_2) \quad . \tag{3.16}$$

Also

$$\lambda_{1\ \text{alone}} = \lambda_1 \left[1 - \lambda_2 (\mu_1 + \mu_2)\right] \tag{3.17}$$

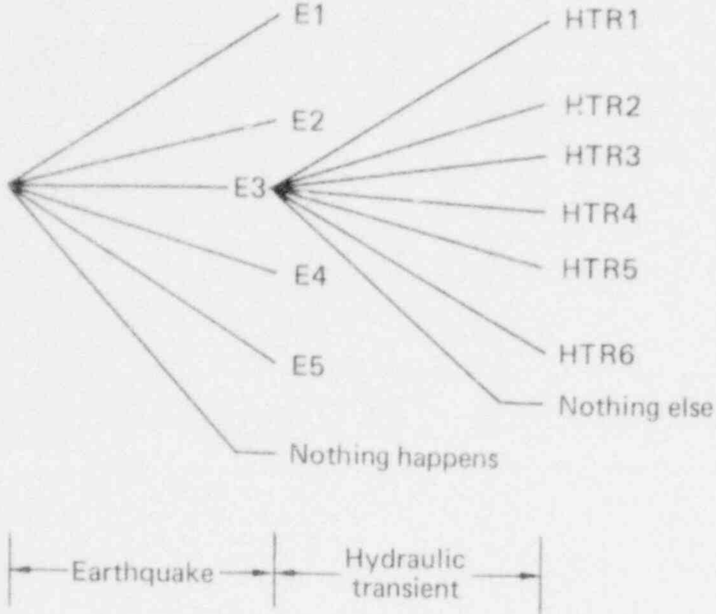
and

$$\lambda_{2\ \text{alone}} = \lambda_2 \left[1 - \lambda_1 (\mu_1 + \mu_2)\right] \quad . \tag{3.18}$$

For the general case of n stationary and independent processes,

$$\lambda_{1+2+\ldots+n} = (n-1)! \left(\prod_{i=1}^{n} \lambda_i \mu_i\right) \sum_{i=1}^{n} \frac{1}{\mu_i} \quad . \tag{3.19}$$

For the example of ESW piping, the load event tree for independent (initial) load is depicted in Fig. 3.4. The mean occurrence rates of different levels λ_E of earthquake are calculated from the results of a seismic hazard analysis of the site. (These are mean occurrence rates of events with peak ground accelerations within a narrow range, e.g., 0.05 to 0.15 g, represented by a single value, e.g., 0.10 g; they are not the usual mean occurrence rates of values equal to or greater than the given level.) Significant motion in an earthquake is assumed to last 10 seconds on the average, i.e., $\mu_E = 10$ s.



Load level	Magnitude	λ/yr
E1	0.10 g	8.00×10^{-4}
E2	0.20 g	1.10×10^{-4}
E3	0.30 g	0.55×10^{-4}
E4	0.40 g	0.30×10^{-4}
E5	0.50 g	0.05×10^{-4}
HTR1	0.25 s	9.15
HTR2	0.50 s	19.90
HTR3	1.00 s	9.25
HTR4	1.50 s	4.55
HTR5	2.00 s	2.55
HTR6	2.50 s	4.60

FIG. 3.4. Load tree for intermittent loads in ESW piping example.

It is assumed that there will be 50 occurrences of hydraulic transients per year. The magnitude of the transient is a function of the valve opening (closing) time. The mean duration μ_{HTR} of the transient is 0.5 s. The mean occurrence rates λ_{HTR} of different levels of hydraulic transient are calculated as shown in Fig. 3.4.

The mean rate of occurrence for any branch of the tree--e.g., load case q of intermittent loads--is calculated using the mean occurrence rates and durations of individual loads. As an example, the load case corresponding to E2 + HTR2 has the mean occurrence rate

$$\lambda_q = \lambda_{E2}\lambda_{HTR2}(\mu_E + \mu_{HTR2}) = \frac{(1.1 \times 10^{-4})(19.90)(10 + 0.5)}{(3.1536 \times 10^7)}$$

$$= 7.3 \times 10^{-10}/\text{yr} \quad .$$

The denominator in the above expression is the number of seconds in a year.

The mean rates of occurrence of E2 alone and HTR2 alone are

$$\lambda_{E2\ alone} = \lambda_{E2} - \lambda_q = (1.1 \times 10^{-4}) - (7.3 \times 10^{-10}) \approx 1.1 \times 10^{-4}/yr \quad ,$$

$$\lambda_{HTR2\ alone} = \lambda_{HTR2} - \lambda_q = 19.90 - (7.3 \times 10^{-10}) \approx 19.90/yr \quad .$$

For load cases that include two or more intermittent loads, the upcrossing rate $\nu_q(y)$ and the a.p.t. probability density function $f_q(y)$ of combined response are derived from the probability density functions and mean upcrossing rates of the individual load responses by utilizing the point-crossing method (Eq. 3.10). Since the point-crossing method requires that the processes to be combined should be stationary and independent, the true finite-duration processes are modified as described by Winterstein.[3] For the case of two loads, the resulting upcrossing formula is

$$\nu_q(y) = p_1 p_2 \left[\nu_{Y_1} * f_{Y_2} + \nu_{Y_2} * f_{Y_1}\right] + p_1(1 - p_2)\nu_{Y_1} + p_2(1 - p_1)\nu_{Y_2} \quad , \tag{3.20}$$

and the probability density function is

$$f_q(y) = p_1 p_2 \left[f_{Y_1} * f_{Y_2}\right] + p_1(1 - p_2) f_{Y_1} + p_2(1 - p_1) f_{Y_2} + (1 - p_1)(1 - p_2)\,\delta(y) \quad , \tag{3.21}$$

where $p_i = \mu_i/(\mu_1 + \mu_2)$; $\delta(y)$ is the Dirac delta function; and μ_i is the mean duration of response 1 or 2. The duration of a single cycle of 1 is $\mu_q = \mu_1 + \mu_2$. This method of calculating $\nu_q(y)$ and $f_q(y)$ can be generalized for cases involving sums of more than two loads.

If we denote the net structural response due to all intermittent loads by $Y_{int}(t)$, its mean upcrossing rate and probability density function are given by

$$\nu_{Y_{int}}(y) = \sum_{q=1}^{Q} \lambda_q \nu_q(y) \mu_q \tag{3.22}$$

and

$$f_{Y_{int}}(y) = \sum_{q=1}^{Q} f_q(y)\ \lambda_q\mu_q + \delta(y)\left(1 - \sum_{q=1}^{Q} \lambda_q\mu_q\right) \tag{3.23}$$

where

$$\mu_q = \sum \mu_i \quad \text{(summation over all loads i in load case q).} \tag{3.24}$$

Total Response. The total response $Y(t)$ of the structural component to continuous and intermittent loads is given by

$$Y(t) = Y_c(t) + Y_{int}(t) \tag{3.25}$$

and

$$\nu_Y(y) = \nu_{Y_c} * f_{Y_{int}} + \nu_{Y_{int}} * f_{Y_c} \tag{3.26}$$

The distribution of the extreme value Y of the response in the life of the component (i.e., T years) is estimated from

$$F_Y(y) \simeq \exp\left[-\nu_Y(y)T\right] \tag{3.27}$$

The probability of the component reaching a limit state at a specific node k is

$$P_{f_k} = P(Y > R^\star) \tag{3.28}$$

$$= \int_0^\infty \left[1 - F_Y(y)\right] f_{R^\star}(r)\ dr \quad , \tag{3.29}$$

where $f_{R^\star}(r)$ is the probability density function of the resistance R of the component at node k, minus the static load effects Y_s; i.e., $R^\star = R - Y_s$. The probability of the component reaching a limit state at any one of K nodes is

$$P_F \approx \max_{k=1}^{K} P_{f_k} \quad . \tag{3.30}$$

Equation 3.30 is a valid approximation because the responses at different nodes arising out of the same load are highly correlated and the variability of loads dominates over that of the component resistance (see Sec. 2.2).

In our specific illustration, the component could reach the limit states of rupture of a cross section, buckling of a restraint, or excessive acceleration.

In calculating the upcrossing rates $\nu_q(y)$ and $\nu_{Y_C}(y)$, the responses in the three local directions $\underline{A}$, $\underline{B}$, and $\underline{C}$ have to be considered. Let X_1 and X_2 be the loads to be combined. Let the moment influence coefficients be $\{c_{1\underline{A}}, c_{1\underline{B}}, c_{1\underline{C}}\}$ and $\{c_{2\underline{A}}, c_{2\underline{B}}, c_{2\underline{C}}\}$ for loads X_1 and X_2, respectively. A normalized moment time history for each direction is selected at random for each load. The mean upcrossing rate $\nu_{Y_{1\underline{A}}}$, and the a.p.t. probability density function $f_{Y_{1\underline{A}}}$ for the moment in direction $\underline{A}$ due to load X_1, for example, are obtained using Eqs. 3.8 and 3.9. The values of ν_q and f_q in the $\underline{A}$ direction are derived as

$$\nu_{q_{\underline{A}}} = p_1 p_2 \left[\nu_{Y_{1\underline{A}}} * f_{Y_{2\underline{A}}} + \nu_{Y_{2\underline{A}}} * f_{Y_{1\underline{A}}} \right] + p_1(1 - p_2)\nu_{Y_{1\underline{A}}} + p_2(1 - p_1)\nu_{Y_{1\underline{A}}} \tag{3.31}$$

and

$$f_{q_{\underline{A}}} = p_1 p_2 \left[f_{Y_{1\underline{A}}} * f_{Y_{2\underline{A}}} \right] + p_1(p - p_2) f_{Y_{1\underline{A}}}$$
$$+ p_2(1 - p_1) f_{Y_{2\underline{A}}} + (1 - p_1)(1 - p_2)\,\delta(y) \quad . \tag{3.32}$$

The resultant moment process at node k is the vector sum of the moment processes in the three local directions:

$$q = (q_{\underline{A}}^2 + q_{\underline{B}}^2 + q_{\underline{C}}^2)^{1/2} \quad . \tag{3.33}$$

The mean upcrossing rate of this process is approximated by finding the mean upcrossing rate of the process, $0.7(|q_{\underline{A}}| + |q_{\underline{B}}| + |q_{\underline{C}}|)$.

3.1.4 Component Fragilities

The component (in the present case, the piping subsystem) designed using the design criteria of Sec. 3.1 has a resistance which is a random quantity; the randomness is a result of the inherent variability in the material property, random errors introduced by the fabrication practices, and the uncertainties in the prediction of limit state resistances.

The piping subsystem could fail because of rupture at a pipe cross section or buckling of a restraint. For this illustration, the cross section is conservatively assumed to rupture when the stress in the piping exceeds the ultimate strength of the material. The ultimate strength of steel is modeled as a lognormally distributed random variable with the median equal to 1.1 times the specified ultimate strength of 60,000 psi (see Ref. 4). The coefficient of variation of the ultimate strength is taken as 0.15.

The component could also fail if a restraint buckles or if the tensile load exceeds the ultimate strength of a restraint. The resistance of a restraint is assumed to be lognormally distributed, with a median value equal to 1.1 times the maximum load capacity for service level D and a coefficient of variation of 0.20.

The limiting acceleration on a butterfly valve is assumed to be distributed as a lognormal random variable with a median equal to 1.25 times the design value for service level C and a coefficient of variation of 0.20.

3.1.5 Implied Probability

The component (or the piping subsystem) designed using the criteria of Sec. 3.1 reaches the ultimate limit state of pipe rupture with a probability P_F (Eq. 3.30). This is the limit state probability implied by the design criteria. Since this probability would vary depending on the geometry and location of the component in the plant, and on the geographic location, a number (m) of components designed according to the design criteria should be analyzed. The components are to be generated by simulation, as described in ¶3.1.2. The implied limit state probabilities P_{F_i} are calculated for these components. A frequency distribution of the implied limit state probability P_F can be obtained (Fig. 3.5). A decision rule for accepting a design criterion could be that the average limit state probability m_{P_F} be

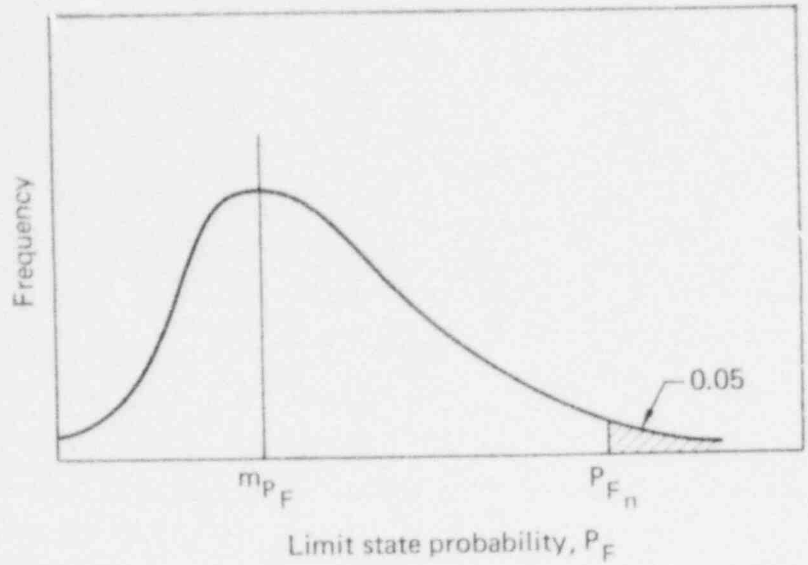


FIG. 3.5. Frequency distribution of the implied limit state probability associated with a given design criterion.

less than the target limit state probability P_T and that a 95 percentile value of P_F should not be more than a specified value P_{F_n}, e.g., $P_{F_n} = 10 \times P_T$.

If the design criteria do not meet these acceptance rules, alternative criteria in the form of load combinations or service levels can be developed as described in the next section.

3.2 DEVELOPMENT OF LOAD COMBINATIONS

The load combination methodology will be used to derive the load and resistance factor values in a set of specified design load combinations of a particular design format. By a design format, we mean the following:

- Enumeration of loads; specification of nominal loads (e.g., postulated or based on some annual non-exceedance probability or mean return period in years).
- Set of design load combinations.
- Method of analysis (linear, nonlinear, equivalent-static, etc.).
- Procedure for combining dynamic responses from different loads (i.e., SRSS, absolute sum of peaks, etc.).
- Procedures for safety checking/proportioning the component.

The load and resistance factors are treated as variables in the format. Their values would be selected such that an acceptable frequency distribution on the component limit state probability is achieved.

3.2.1 Illustration

An example of a design format for the design of ESW piping (¶3.1.1) is given below.

Loads	Nominal Loads
Weight, W	Weight, W
Seismic, E	Seismic, OBE and SSE
Hydraulic transient, HTR	Hydraulic transient, HTR_N
Thermal, TH	Design pressure, P_d
Pressure, P	Thermal load, TRNG

Load Combinations

$$\phi_{11}R_1 \geq \gamma_P c_P P_d + \gamma_W c_W W \tag{3.34}$$

$$\phi_{12}R_1 \geq \gamma_P c_P P_d + \gamma_W c_W W + \gamma_{E_{10}} c_{E_0}(OBE) \tag{3.35}$$

$$\phi_{12}R_1 \geq \gamma_P c_P P_d + \gamma_W c_W W + \gamma_H c_H (HTR_N) \tag{3.36}$$

$$\phi_{12}R_1 \geq \gamma_P c_P P_d + \gamma_W c_W W + \gamma_{TH} c_{TH}(TRNG) \tag{3.37}$$

$$\phi_{13}R_1 \geq \gamma_P c_P P_d + \gamma_W c_W W + \gamma_{E_{11}} c_{E_0}(OBE) + \gamma_{H_1} c_H (HTR_N) \tag{3.38}$$

$$\phi_{14}R_1 \geq \gamma_P c_P P_d + \gamma_W c_W W + \gamma_{E_{12}} c_{E_s}(SSE) \tag{3.39}$$

$$\phi_{21}R_2 \geq \gamma_{E_{21}} c_{E_{oA}}(OBE) \tag{3.40}$$

$$\phi_{22}R_2 \geq \gamma_{E_{22}} c_{E_{SA}}(SSE) \tag{3.41}$$

$$\phi_{23}R_2 \geq \gamma_{E_{23}} c_{E_{oA}}(OBE) + \gamma_{H_2} c_{H_A}(HTR_N) \tag{3.42}$$

$$\phi_{24}R_2 \geq \gamma_{H_3} c_{H_A}(HTR_N) \tag{3.43}$$

The ϕ's are the resistance factors, γ's are the load factors, and c's are the influence coefficients. R_1 is the resistance of the component under failure modes corresponding to the ultimate limit state of rupture. The resistance factors on R_1 are different for different load combinations (Eqs. 3.34

through 3.39). The load factor value on a load effect--e.g., OBE and HTR--could vary depending on the load combination. The product of the influence coefficient and nominal load, called the load effect, refers to the imposed stress, response, moment, etc. The resistance of a component correspondingly signifies strength, moment capacity, etc. In the formulas above, the load effect and resistance are measured in the same units.

An examination of these load combination equations would reveal similarities between current practice and the load factor format. Equation 3.34 would correspond to the sustained load (design) condition. Equations 3.35, 3.36, and 3.37 are equivalent to service level B. Equations 3.38 and 3.39 may be considered equivalent to service level C. The product ϕR can be correlated with the allowable stress for the particular service level. Current ASME-based practice implicitly specifies the values of all the load factors γ as unity. The values of ϕ and γ in Eqs. 3.34 through 3.39 are to be derived for a target limit state probability P_T. Equation 3.34 could also be included as a load combination to check a functional limit state condition.

R_2 is the nominal acceleration (measured at a valve or in-line equipment) that the component can withstand. In terms of current design rules, the quantity $(\gamma_{E_{21}} c_{E_{oA}} OBE/\phi_{21})$ is the limiting acceleration due to an OBE. A similar remark holds for the limiting accelerations for other loads and load combinations (Eqs. 3.41 through 3.43). Such limiting acceleration values are specified in the local axes $\underline{A}$, $\underline{B}$, and $\underline{C}$. The values of ϕ and γ are derived for a specified probability of reaching the functional limit state of excessive acceleration.

Analysis. The method of analysis is to be linear elastic; the response to earthquake loads is obtained using response spectrum analysis. The hydraulic transients are analyzed using time-history integration.

Response Combinations. Dynamic responses in Eq. 3.25 should be combined according to the SRSS rule.

Methods of Proportioning. The minimum thickness t_m is selected as per Eq. 3.1. At each node in the piping, the load combinations given in Eqs. 3.34 through 3.39 have to be satisfied. For example, Eqs. 3.34 and 3.38 would be expanded as

$$\frac{\gamma_P P_d D_o}{4t_n} + \frac{0.75i}{Z}\left[(\gamma_W c_W W)^2_{\underline{A}} + (\gamma_W c_W W)^2_{\underline{B}} + (\gamma_W c_W W)^2_{\underline{C}}\right]^{1/2} \le \phi_{11} S_h \quad , \tag{3.44}$$

$$\frac{\gamma_P P_d D_o}{4t_n} + \frac{0.75i}{Z}\Bigg[\left\{\gamma_W c_W W + \sqrt{\left[\gamma_{E_{11}} c_{E_o}(OBE)\right]^2 + \left[\gamma_{H_1} c_{H_o}(HTR_N)\right]^2}\right\}^2_{\underline{A}}$$

$$+ \left\{\gamma_W c_W W + \sqrt{\left[\gamma_{E_{11}} c_{E_o}(OBE)\right]^2 + \left[\gamma_{H_1} c_{H_o}(HTR_N)\right]^2}\right\}^2_{\underline{B}}$$

$$+ \left\{\gamma_W c_W W + \sqrt{\left[\gamma_{E_{11}} c_{E_o}(OBE)\right]^2 + \left[\gamma_{H_1} c_{H_o}(HTR_N)\right]^2}\right\}^2_{\underline{C}}\Bigg]^{1/2}$$

$$\le \phi_{13} S_h \quad . \tag{3.45}$$

The load combinations given by Eqs. 3.40 through 3.43 are used to ensure that the design acceleration of the valve or in-line equipment is not exceeded. $c_{E_{OA}}$, $c_{E_{SA}}$, and c_{H_A} are the influence coefficients that amplify the response (acceleration) at the equipment location for input motions of OBE, SSE, HTR, and MTR. If the accelerations for these combinations are less than ϕ times the capacity of the equipment, the piping subsystem is acceptable. If this is not so, a modification to the system, such as altering the fundamental frequency of the equipment and providing additional restraints, is necessary.

Load and Resistance Factors. As noted above, all the features of the selected design format have been specified. Load and resistance factors are the only variables in this format. They are to be selected such that the components designed using this design format have acceptable limit state probabilities. How closely the component limit state probability matches the target limit state probability is measured in this illustration by a function of these two probabilities. Since this measure varies over all future component design, called "data space" $\mathcal{D}$, an expected value of the squared difference is defined as

$$\Omega(\phi,\underset{\sim}{\gamma}) = \sum_{\underset{\sim}{\omega}\in\mathcal{D}} f(\underset{\sim}{\omega})\left[\frac{\log P_F(\underset{\sim}{\omega}) - \log P_T}{\log P_T}\right]^2 \quad , \tag{3.46}$$

where $\underset{\sim}{\omega}$ is a point in the data space, i.e., a class of component designs. $f(\underset{\sim}{\omega})$ is a weight and/or frequency measure associated with the data point $\underset{\sim}{\omega}$. $P_F(\underset{\sim}{\omega})$ is the probability of reaching the limit state for the class of components. P_T is the target limit state probability.

The optimal values of ϕ and γ are derived by minimizing the objective function Ω. This minimization, called "code optimization,"[5] is a nonlinear programming problem and can be solved using well-known hill-climbing algorithms.

If different limit states are to be considered, the objective function should be modified as

$$\Omega(\underset{\sim}{\phi},\underset{\sim}{\gamma}) = \sum_{\underset{\sim}{\omega}\epsilon 0} \left\{ f(\underset{\sim}{\omega}) \sum_{\ell=1}^{L} k_\ell \left[\frac{\log P_{F_\ell}(\underset{\sim}{\omega}) - \log P_{T_\ell}}{\log P_{T_\ell}} \right]^2 \right\}, \tag{3.47}$$

where ℓ refers to a limit state (e.g., ultimate, functional, and damage), k_ℓ is the weighting factor given to limit state ℓ, and P_{T_ℓ} is the target probability for limit state ℓ.

The above procedure results in load combinations that provide components which have, on the average, limit state probabilities approximately equal to the target values. In some instances, one may want a criterion with absolute upper limits on the component limit state probabilities. Such an additional restriction can be accommodated in the code optimization procedure by minimizing Ω subject to the limit state probability constraints.

In the context of the example of the ESW line, 8 resistance factors and 13 load factors must be derived for target limit state probabilities of 10^{-8}/yr (ultimate) and 10^{-5}/yr (excessive acceleration). The weighting factors k_ℓ are taken to be 2 and 1, respectively, for ultimate and functional limit states.

The objective function Ω is evaluated for 20 sampled component designs. The frequencies of occurrence $f(\underset{\sim}{\omega})$ of each of these designs are assumed to be equal (= 1/20).

3.2.2 Alternate Formats

The above procedure of deriving optimal load and resistance factors requires the specification of a design format. As noted earlier, the design format consists of the specification of nominal loads, design load combinations, method of analysis, method of combining dynamic responses, and procedures for calculating the component resistances.

Selection of a design format--more specifically, the design load combinations--is an area of continued debate within code committees and between the regulatory agency and the industry. The primary advantage of the load combination methodology described herein is that the load and resistance factor values are adjusted for any selected set of load combinations to achieve the component target limit state probabilities. The methodology does not require any new load combinations or any documented justification for the load combinations. However, a judicious choice of load combinations to cover different design situations would help to approach the target component reliabilities more closely. In other words, the higher degrees of freedom--i.e., the number of load and resistance factors--would generally lead to lower minimum values of Ω. For any given design format, the load and resistance factor values are derived by minimizing Ω. It is generally possible to obtain a lower value of Ω by selecting a different, "better" design format. The optimal load and resistance factor values are obtained within a design format by the optimization process. Of the several design formats, the "best" format can be judged by comparison of their respective (minimum) Ω values. Practical issues are also important, however. The load combinations should be selected such that the number of resulting design rules is kept to a practical minimum to facilitate routine design. The following are some alternate design formats that need to be studied.

ASME Design Format. The ASME Boiler and Pressure Vessel Code, Section III, Division 1, Nuclear Power Plant Components (ASME Code) governs the design of vessels, pumps, valves, piping, steel containment, and component supports. The ASME Code defines six conditions for load combinations: design, service levels A, B, C, and D, and testing. The philosophy in the ASME Code is to place limits on stress for these conditions for which various unfactored load effects are combined. The four service levels allow combinations of loads of increasing severity and decreasing frequency of occurrence to be placed in separate categories with different stress limits. Load combinations are not included in the code, and they may vary from component to component and from plant to plant. However, the service levels and the stress limits are chosen arbitrarily; the resulting reliabilities may vary from component to component and from plant to plant.

The ASME format can be preserved by keeping all the load factors equal to unity and evaluating the allowable stresses (ϕR) for target limit state probabilities. The load combinations, for the example of ESW piping, would then be as follows:

$$\phi_{11} S_h \geq c_P P_d + c_W W \quad , \tag{3.48}$$

$$\phi_{12} S_h \geq c_P P_d + c_W W + c_{E_o}(OBE) \quad , \tag{3.49}$$

$$\phi_{12} S_h \geq c_P P_d + c_W W + c_{H_o}(HTR_N) \quad , \tag{3.50}$$

$$\phi_{12} S_h \geq c_P P_d + c_W W + c_{TH}(TRNG) \quad , \tag{3.51}$$

$$\phi_{13} S_h \geq c_P P_d + c_W W + c_{E_o}(OBE) + c_{H_o}(HTR_N) \quad , \tag{3.52}$$

$$\phi_{14} S_h \geq c_P P_d + c_P W + c_{E_S}(SSE) \quad , \tag{3.53}$$

$$\phi_{21} R_2 \geq c_{E_{oA}}(OBE) \quad , \tag{3.54}$$

$$\phi_{22} R_2 \geq c_{E_{SA}}(OBE) \quad , \tag{3.55}$$

$$\phi_{23} R_2 \geq c_{E_{oA}}(OBE) + c_{H_A}(HTR_N) \quad , \tag{3.56}$$

$$\phi_{24} R_2 \geq c_{H_A}(HTR_N) \quad , \tag{3.57}$$

where R_2 is the nominal acceleration that the component can withstand.

This alternative may be a very practical one, involving the fewest changes from current practice; however, the flexibility in matching the target limit state probabilities is rather limited because of the relatively small number of degrees of freedom in this format. The price paid for this practicality will be measured in part by the larger value of Ω that can be anticipated.

Different Response Combination Procedures. Current practice has been to combine dynamic responses from different transient loads using the SRSS procedure.[6,7] This approach has been defended on the grounds that the SRSS value would not be exceeded in about 75 to 85 percent of the transient response combinations. It has also been argued that the dynamic reserve margins not explicitly accounted for in the current ASME Code would compensate for excursions above the SRSS value.

Since consistency in the design criteria is achieved by making the limit state probabilities of different components equal, a basis for judging between the SRSS procedure or the ABS procedure is the minimum Ω value for each procedure. If the two Ω_{min} values do not differ significantly, then it does not matter which procedure is used. Whichever procedure is used, the load and resistance factor values are adjusted accordingly.

Event Decoupling. In Project I of the Load Combination Program, mechanistic arguments are being used to demonstrate that seismic events may not cause large instantaneous pipe breaks leading to loss of coolant accident (LOCAs). Also, the probability of rupture of a seismically designed pipe under seismic loads is shown to be very small.

An alternative approach is to compare two design formats, one that includes the combination of earthquake and LOCA loads, and the other with no such combination. For these two design formats, the optimal load and resistance factors are evaluated for a target component limit state probability of P_T. Note that the probability analysis will in both cases properly include the probabilities that LOCA and earthquake occur simultaneously. The design format that has a lower value of the minimum objective function Ω_{min} (Eq. 3.47) is judged to be the "better" alternative. It may be concluded from such a study that the difference between Ω_{min} values for the two formats is not significant, i.e., not large enough to warrant the use in design of earthquake and LOCA load combination.

Use of Multiple Load Levels. The industry practice has been to use two levels of earthquake, OBE and SSE. By this, it is presumed that the salient features of the entire spectrum of earthquake levels are included in the design. However, questions such as "Should the OBE govern the design of nuclear components?" and "What should be the mean recurrence interval of the OBE?" are raised. Answers to the first question can be sought by evaluating two design formats--one with two nominal levels of earthquake and the other with just one nominal level of earthquake. If the difference between Ω_{min} values for the two formats is not significant, the use of multiple load levels may not be warranted. For a given number of seismic design levels, say two, one can try different mean return period definitions of the OBE and the SSE and compare Ω_{min} values to determine the best choices.

3.3 CALIBRATION

The load combination methodology described herein requires as input the target limit state probability P_T. This could be derived by performing a system reliability analysis. It is possible to assign the reliabilities of different components in the safety systems to achieve a specified acceptable plant risk. This aspect will be studied in depth in Phase II of the LCM Project.

However, it is of immediate interest to know the reliabilities implied by current design criteria. For this purpose, different types of components should be designed for the ASME Code requirements and the limit state probabilities should be evaluated. If these limit state probabilities of components that are at different locations but that perform essentially identical functions show much variation, it would mean that the current design criteria are not consistent. By studying these component limit state probabilities, target values of P_T can be established for each component. It may be necessary to classify components into groups for practical reasons. A set of load combinations for the design of each group (e.g., Class I, II, and III piping) may be obtained using the procedure described in Sec. 3.2. This technique of assessing the implied reliabilities in components designed according to current codes and adjusting the parameters in a probabilistic design methodology to achieve comparable reliabilities is called "code calibration."[8] It has been used in developing the modern probabilistic codes for building design.[4] However, the procedure should be used judiciously for developing design criteria for nuclear components, since experience with nuclear design codes is limited. Yet, the calibration studies are a useful starting point in developing load combination values and in achieving any desired uniformity of component reliabilities.

4. SYSTEMS ANALYSIS METHODOLOGY

The choice of a probabilistic approach to load combinations requires that a target limit state probability be established for each component and structural element before the design can proceed. The purpose of the systems analysis is to provide a methodology whereby the required target probabilities can be determined.

The assignment of target limit state probabilities would be greatly simplified if

- The operations of nuclear power plant safety systems were not interactive following an event that could lead to radioactive release.
- Redundancy of components were not provided for within safety systems.
- Components and structures could be assumed to fail independently in a combined loading environment.

Since none of these conditions is operative, the methodology must consider the dependent nature of failure between components, as well as the system-level interactions and component-level redundancies. The approach that is proposed creates requirement for some degree of safety analysis during the preliminary design stage.

The requirement to establish target limit state probabilities at the preliminary design stage requires an approach that is the reverse of the generally accepted approach to systems safety analyses. Given that the final design has been established, the component limit state probabilities can be evaluated first, then the subsystem and finally the system, in order to quantify the probability of failure for the completed plant design. This can be called the bottom-up approach. In contrast, the need for target limit state probabilities prior to final design requires that a failure probability for the plant first be established and then be apportioned to the systems, the subsystems, and finally the components. This allocation at the component level, which can be called the top-down approach, must be such that the required plant limit state probability is not exceeded.

The problem with the top-down approach is that there are an infinite number of combinations of component probabilities that will satisfy the required plant limit state probability. Consequently, a rational methodology must be developed which produces component target limit state probabilities that meet additional criteria, such as risk, minimum cost, etc. The inclusion of these additional criteria is necessary in order to constrain the allocation problem somewhat to a specified region for solution.

Three approaches to allocation were considered, and each is examined in subsequent sections. Before proceeding, however, it is worthwhile to note some of the special problems or considerations involved in developing the methodology. First, it must be acknowledged that, in systems failing because of seismic or other regional environments, there will be a great deal of correlation in the load intensities between neighboring components. This leads to a problem of statistical correlation in the limit state probabilities between components. Correlation in load intensities may, for example, increase the probability of system limit states and thus, if ignored, will produce misleading conclusions about the true capability of the system. (The comparison is made with the assumption of noncorrelated load intensities in the same loading environment.) Furthermore, the correlation in load intensities between components will not be uniform throughout the plant and will be difficult to predict unless a comprehensive analysis, such as that to be performed by the SEISIM program for the Seismic Safety Margins Research Program (SSMRP), is conducted. (SEISIM allows the computation of system limit state probabilities in a seismic environment, taking into consideration the correlated intensities of local loads.)

Another difficulty is that increased reliability is not achieved with equal ease for all components. Some are expensive to improve from a reliability standpoint, and this must be considered in the allocation process. Other considerations include the sensitivity of system limit state probabilities to the failure of individual components. Given that the failure of a system is dominated by the failure of a few components, it makes sense to limit changes in the initial allocation to only these dominant components.

4.1 AN IDEAL APPROACH TO ALLOCATION

In pursuing an allocation methodology, we first evaluated a so-called ideal approach, which would handle all of the considerations listed above. This ideal approach is outlined in the flow diagram of Fig. 4.1; it consists

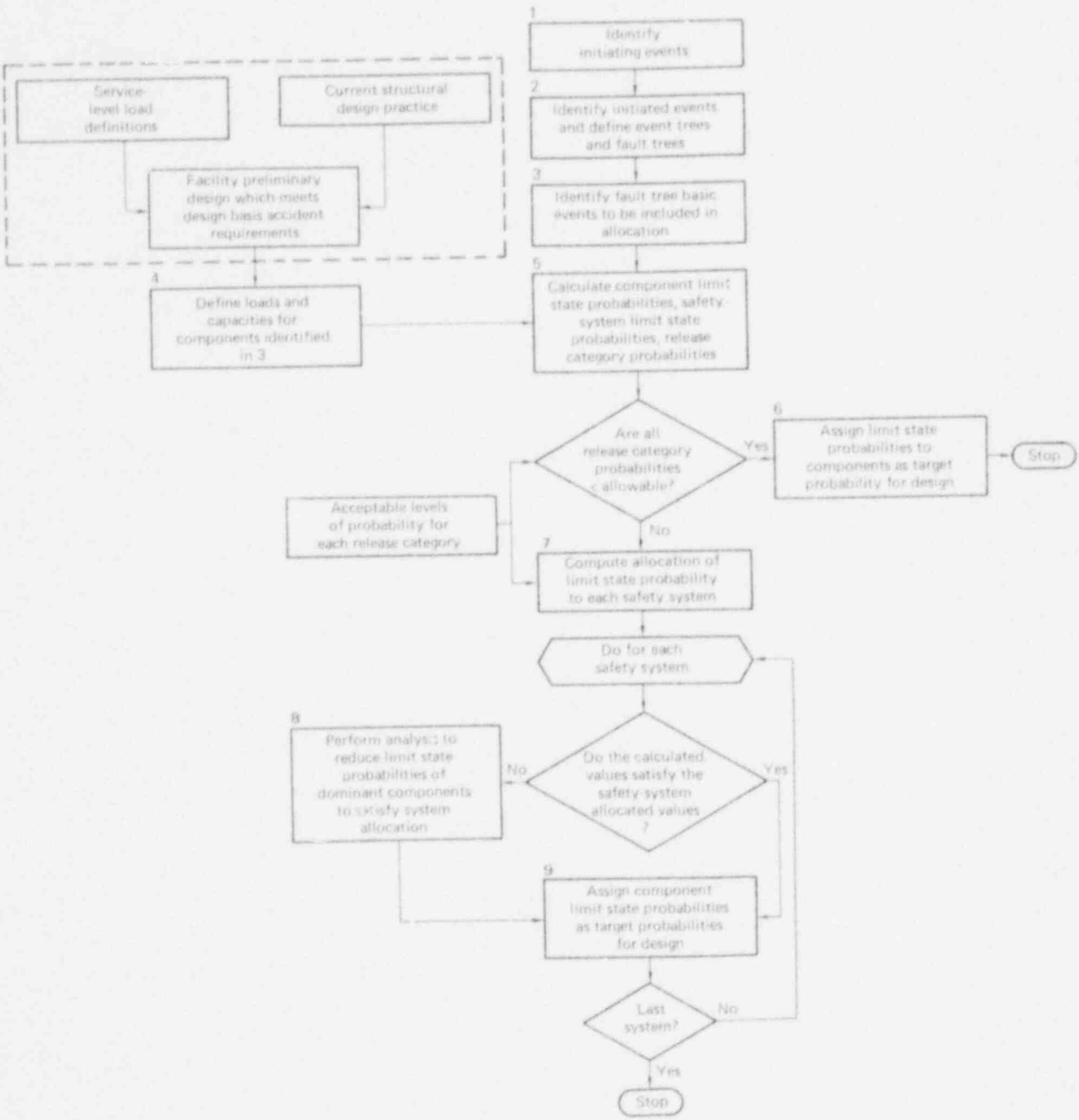


FIG. 4.1. Flowchart for ideal allocation methodology.

of nine steps. The procedure starts with a knowledge of the preliminary facility design which meets presently required design basis accident (DBA) requirements. Based on this preliminary design, it would be possible to develop statistical descriptions of local responses throughout the facility and to define component capacities (fragilities). Event and fault trees are then drawn up (step 2) and used to perform a system failure analysis (step 5), using a bottom-up procedure which starts with the computation of the component limit state probabilities. The system failure analysis would also compute probabilities of radioactive release in each of several release categories.

At this point in the allocation procedure, there is a requirement for a definition of acceptable risk. Assuming that acceptable risk can be defined by limiting probabilities on each of the release categories, it is possible to determine from this initial analysis whether the range of initiated events is adequately covered, from a risk standpoint, by the proposed design. If the risk criteria are met, then calculated component limit state probabilities become the assigned target values for final design (step 6).

If the risk criteria are not met, the procedure requires identification of those safety systems and components which contribute most to the exceedance of release category probabilities. The focus of the allocation procedure is now on those components which require reliability improvement. The approach to allocation of target probabilities to this final group of components is accomplished by means of a sensitivity analysis of the system limit state probability to changes in component capacities. The results of this sensitivity analysis are incorporated into procedures (steps 7 and 8) which use the acceptable release category probabilities as constraints and which optimize component allocations, considering minimization of cost, risk of high-consequence releases, or some other attribute. The result of this optimization is an allocation of target probabilities (step 9) for those components that had been identified as requiring reliability improvement. These target probabilities are now used in the final detailed design, using the structural reliability methodology described in the previous chapters. The results of this approach is a design that is based initially on current practice that has been improved in those areas necessary to meet risk objectives for the power plant.

The problem with this approach is that a great deal of design work must take place before load combinations and detailed design can even become a consideration. In fact, there are basically two design cycles with an intervening optimization. This may be more drawn out, complicated, and expensive than would be acceptable within the industry. Thus, a reasonable improvement or simplification would be to modify the methodology such that only one structural design phase is necessary. To do this, however, means that target probabilities would have to be assigned before any knowledge exists on the probabilistic interaction of the failure of the components in the system (i.e., before any knowledge has been developed about statistical correlations between loads and, perhaps, between capacities).

4.2 A SIMPLE ALLOCATION METHODOLOGY

In contrast to the ideal allocation procedure that has been suggested in the preceding paragraphs, a simple allocation procedure will now be described (Fig. 4.2).

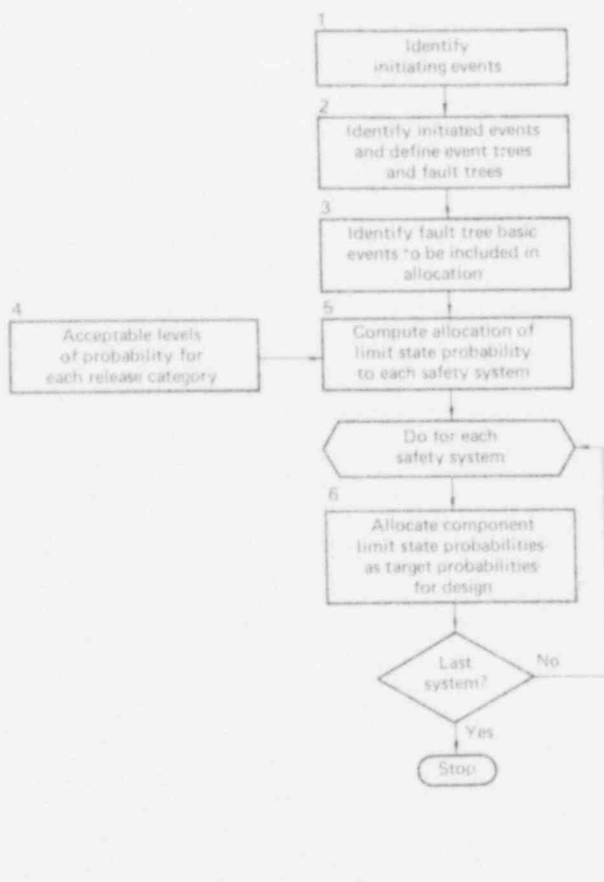


FIG. 4.2. Flowchart for simplified allocation methodology.

The first three steps in this simplified procedure are identical to those outlined for the idealized procedure. A fundamental difference in approach has been established, however, wherein the simple procedure does not require the specification of expected component loads and capacities from a preliminary design analysis.

Instead, based upon the allocated limit state probabilities for systems contributing to the release category probabilities, a limit state probability is allocated to each safety system component. This simple allocation procedure could be completed rather rapidly in one of the two following ways:

- Assign equal probabilities to each basic event as called out by the fault trees for each safety system. Assuming independence between basic events, a simple iteration is all that is required in order to arrive at the desired solution.
- A variation of the above would be to assign equal probabilities to each gate of the fault tree and then assign equal probabilities to each basic event contributing to each gate, such that the top event allocated value is satisfied. This procedure is likely to result in a more realistic allocation than the first one.

Neither of the above simple approaches considers (a) the cost of obtaining the desired reliability for each component, (b) the relative component contributions to system failure, (c) the effects of statistical correlations between component loads in a combined loading environment, or (d) the effects of statistical correlations between component capacities. While the effect of (d) can perhaps be expected to be relatively insignificant, the effects on the respective allocations associated with (a), (b), and (c) are likely to be quite significant.

4.3 A PRAGMATIC APPROACH TO ALLOCATION

Due to the impracticalities of the idealized approach and because the simplified procedure is likely to result in an unrealistic allocation, a third approach is suggested. This pragmatic approach is outlined in the flow diagram of Fig. 4.3. Essentially, this approach is similar to that outlined in Fig. 4.1, except that step 4 does not require the definition of component

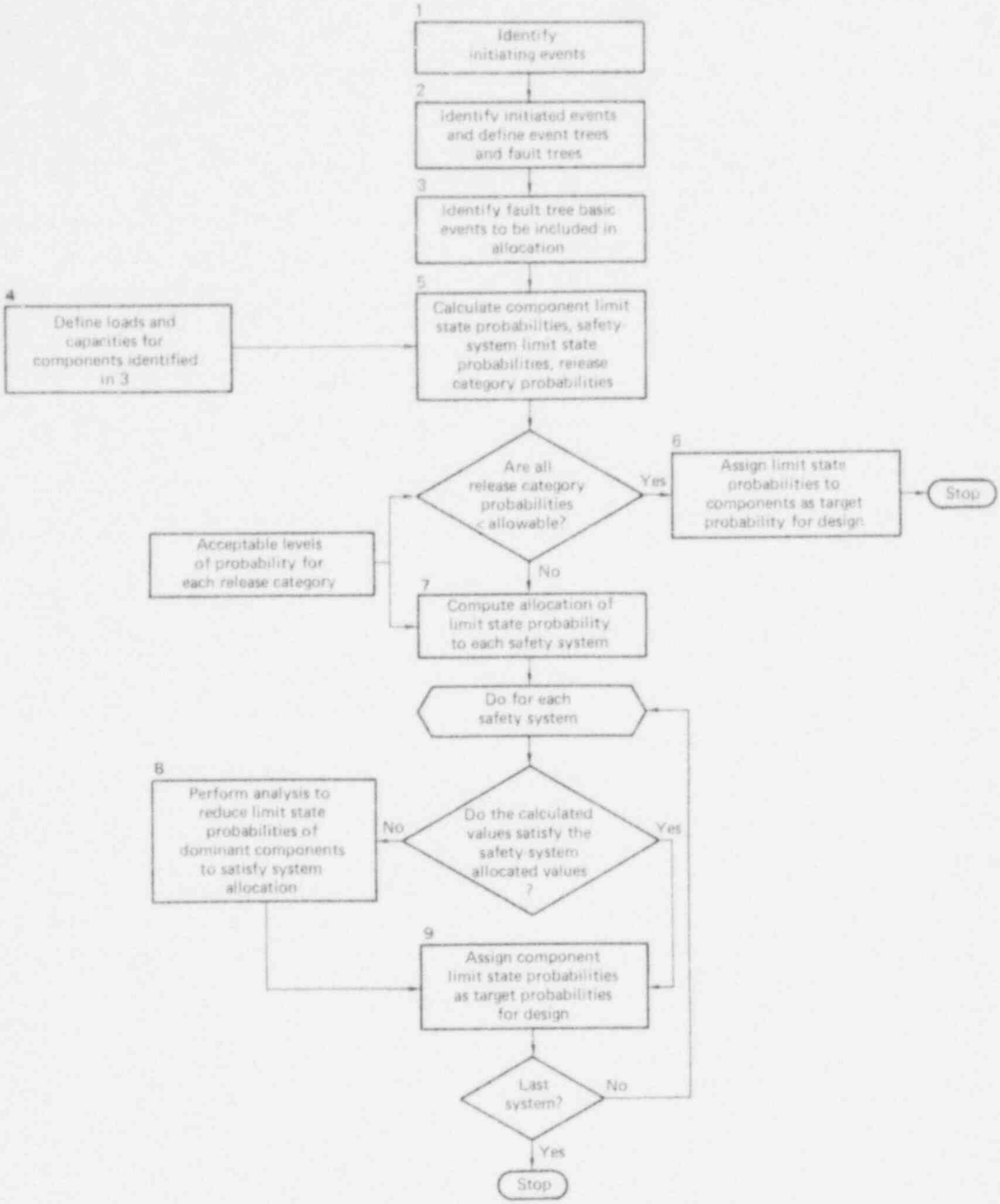


FIG. 4.3. Flowchart for pragmatic allocation methodology.

loads and capacities. This approach has the appealing advantage of not requiring a two-step design procedure. Furthermore, as will become clear, it will in some degree handle the inherent weaknesses of the simplified approach.

Instead of defining component loads and capacities, step 4 now requires the specification of what is called a safety index β for components identified by the safety-system fault trees. The component safety index β will now be defined in terms of its relationship with the component's failure probability. If the capacity of a component is designated by R and the peak measured component response (in a combined loading environment) is designated by Y, then failure occurs when $Y > R$. If the probability distributions of both Y and R are normal and statistically independent, then failure occurs when $Y - R = Z > 0$. $Y - R$ is normally distributed with mean $\mu_Z = \mu_Y - \mu_R$ and variance $\sigma_Z^2 = \sigma_Y^2 + \sigma_R^2$. The probability of failure is then

$$P_f = P(Z > 0) = \frac{1}{\sigma_Z\sqrt{2\pi}} \int_0^{\infty} \exp\left[-\frac{1}{2}\left(\frac{Z - u_Z}{\sigma_Z}\right)^2\right] dZ$$

$$= 1 - \Phi(-\mu_Z/\sigma_Z) = 1 - \Phi(-\beta) \quad , \qquad (4.1)$$

where $\Phi()$ is the standard normal cumulative probability distribution.

By specifying β in step 4, based on current design practice with similar component designs, the limit state probability of each component in the fault tree can be calculated. The limit state probability computed by the above equation is referred to as a "notional" probability. It should be interpreted in a sense relative to the probabilities computed for other components. However, by calculating the system limit state probabilities using the notional component probabilities, provision has been made for the relative component contributions to system failure. Furthermore, by using this approach, provision can be made for the relative difficulty (cost or whatever) in achieving a subsequent reduction in component probabilities in order to satisfy the allocated system-level value.

If the system-level probability allocation is satisfied by the notional component probabilities (i.e., without resort to step 8 of Fig. 4.3), then these notional values become the target values for final design. If step 8 must be undertaken, then the β values of the components which dominate the system limit state probabilities must be increased. By increasing the β values of the dominant components, according to some rationale, their limit state probabilities will be reduced. The final set of β values which result in satisfaction of the system-level allocated probability value will be translated into target probabilities for design.

4.4 EXTENDING THE PRAGMATIC APPROACH

The above procedure is a significant improvement on the simplified approach of Fig. 4.2; however, an extension of the approach is required to handle the correlations between component responses in a combined loading environment. The effect of correlated component responses (and to a lesser extent correlated component capacities) will be, in general, to increase the limit state probability of safety systems. The allocation procedure must, therefore, include these effects if realistic assignments are to be made. (It must be made clear, however, that the effects of correlation are not fully understood. Part of the requirement of the systems analysis will be to measure its impact on the assignment of target probabilities.)

It is suggested that the approach embodied in Fig. 4.3 can be improved by drawing on the experience gained in the SSMRP and other programs. The SSMRP, for example, will provide information on the effect of correlated local responses on structural and component failures. This work on the SSMRP is associated entirely with the responses of nuclear plant structures and systems to a seismic environment. Different combined loading environments may produce quite different relationships in the behavior of components, structures, and systems. At the very least, however, the SSMRP will provide insights into how different levels of correlation will affect system failure probabilities.

Depending on the nature of the combined loading environment, it may be practical to use what are called regional correlations. For example, the effect of a LOCA will be to increase the loading on certain safety-related equipment within the reactor containment. The responses of this equipment, subjected to the additional LOCA loadings, will be interrelated; thus, a large degree of regional correlation will be evident in this area. A further possibility would be to use ranges of correlation, in a sensitivity sense, in order to measure its effects on system failure probabilities.

The introduction of these approaches to correctly handling the effects of correlation in a combined loading environment will provide target probabilities for the structural reliability analysis in which confidence can be placed. Further details of the approach to computing target probabilities, including the effects of correlation, are included in the appendixes. The approach draws on the experience gained with the SEISIM program for the SSMRP and makes use of an analysis based on the multivariate normal (or lognormal) distribution.

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*Available for purchase from the NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission, Washington, DC 20555, and the National Technical Information Service, Springfield, VA 22161.

APPENDIX A: COMPUTATION OF TARGET PROBABILITIES INCLUDING THE EFFECTS OF CORRELATION

The overview of the major steps of the methodology, presented in Chapter 4, introduced the need for some form of acceptable risk criteria on which to base the allocation methodology. The allocation methodology described here assumes a plant and site risk profile related to the curies of ^{131}I released.

The ultimate goal of the procedure is to establish component limit state probability allocations as a basis for subsequent detailed design. These component-level allocated values must result in a plant design which meets or exceeds an acceptable plant risk level over the complete sample space of initiated events.

Section A.1.1 outlines the allocation methodology at the system level, introducing the use of event trees. Section A.1.2 further develops the methodology, with the use of fault trees to aid in the allocation at the component level.

A.1.1 SYSTEM-LEVEL ALLOCATION METHODOLOGY

A.1.1.1 Power Plant Risk Profile

The system-level allocation procedure, developed in subsequent sections, makes use of a risk profile for the power plant that can be defined in the form of a cumulative distribution function F(C). One such function is shown in Fig. A.1, where the risk measure is considered to be curies of ^{131}I released outside the plant boundary. The discretized risk profile of Fig. A.2 is obtained from Fig. A.1 in the following way. With reference to the values of C at points a and b in Fig. A.1, let

$$P(C \geq b) = F(b)$$

and

$$P(C \geq a) = F(a)$$

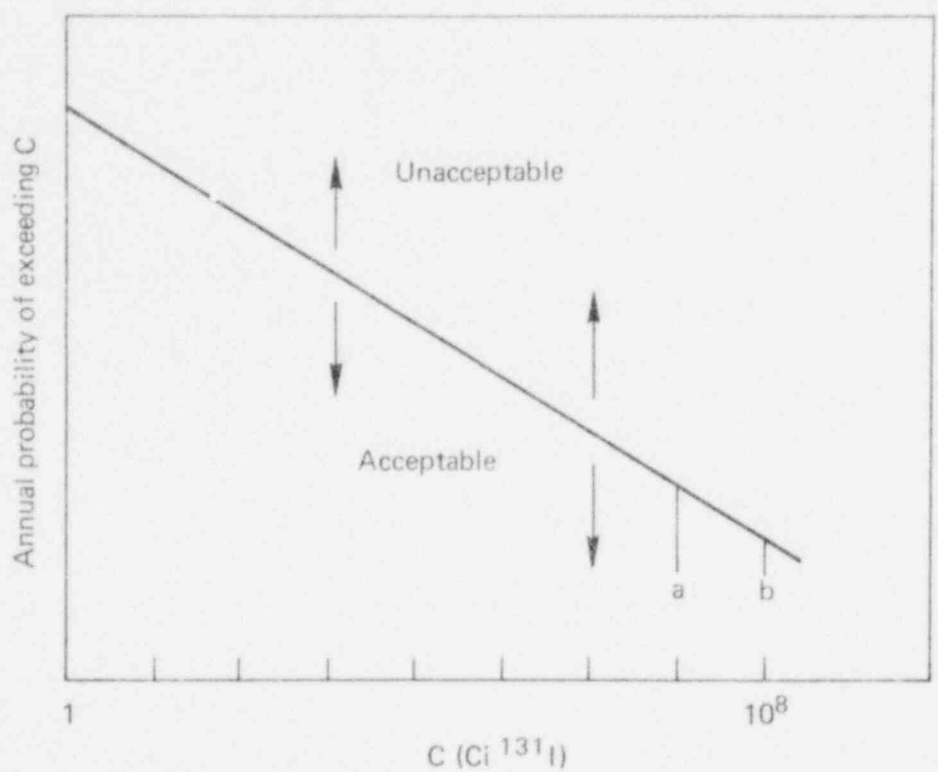


FIG. A.1. Plant and site risk profile. The significance of points a and b is discussed in the text.

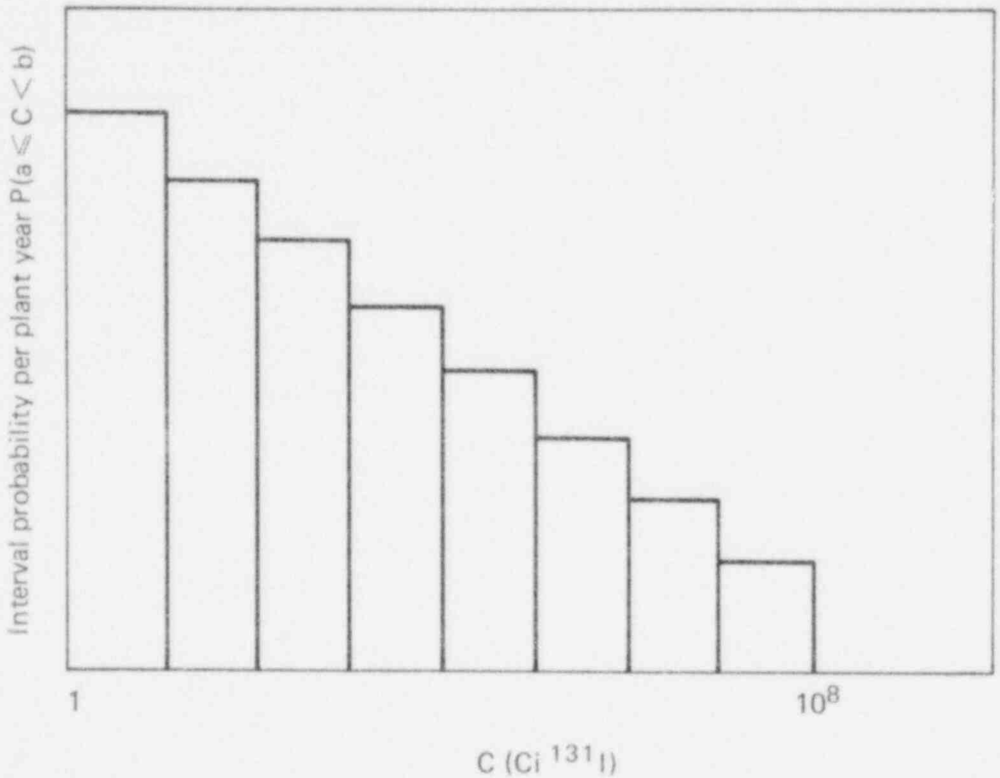


FIG. A.2. Discretized plant and site risk profile.

Then

$$P(a \leq C < b) = F(a) - F(b) \tag{A.1}$$

The risk profile can therefore be discretized into any number of divisions, depending on the choices of abscissa values a and b.

A.1.1.2 The Use of Event Trees

The system-level allocation will make use of the discretized risk profile, but first, some further concepts must be introduced. The discussion that follows centers on an allocation scheme which considers the interactions among safety systems in response to a potentially dangerous initiated event.

In order to introduce the methodology as simply as possible, only two (hypothetical) initiated events are considered from the complete sample space of all potential initiated events. These two initiated events are shown intersecting in Fig. A.3, which allows for the fact that initiated events X and Y could occur simultaneously as a result of a common initiator such as an earthquake. Event X could, for example, be a large loss of coolant accident (LOCA) and event Y a smaller LOCA. The event X Y is the simultaneous occurrence of X and Y, which may not be equivalent to event X occurring alone in terms of the behavior of the reactor core.

In order to mitigate the effects of events such as loss of primary coolant, safety systems are installed in nuclear power plants. For this discussion, up to seven such systems are required to operate in order to ensure safe reactor shutdown after an event occurs. (See Figs. A.4 and A.5.) Safety systems which do not operate after an event occurs will result in an accident with the potential for release of fission products to the environment. Depending upon which combinations of safety system failures and successes occur, different accident paths are possible. Figures A.4 and A.5 outline in event tree (decision tree) format the accident sequence paths possible as a result of the two assumed initiated events (IE) 1 and 2, for "X" and "Y." A total of 26 accident paths are possible: 12 as a result of "X" and 14 as a result of "Y." Discussed below are 11 for "X" and 13 for "Y."

Each accident path probability can be described in terms of safety system involvement as required to mitigate the effects of the initiated event. For

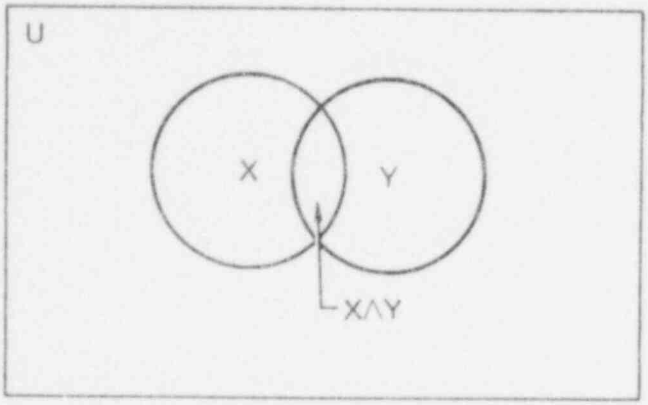


FIG. A.3. Initiated events X and Y as subsets of all possible events U.

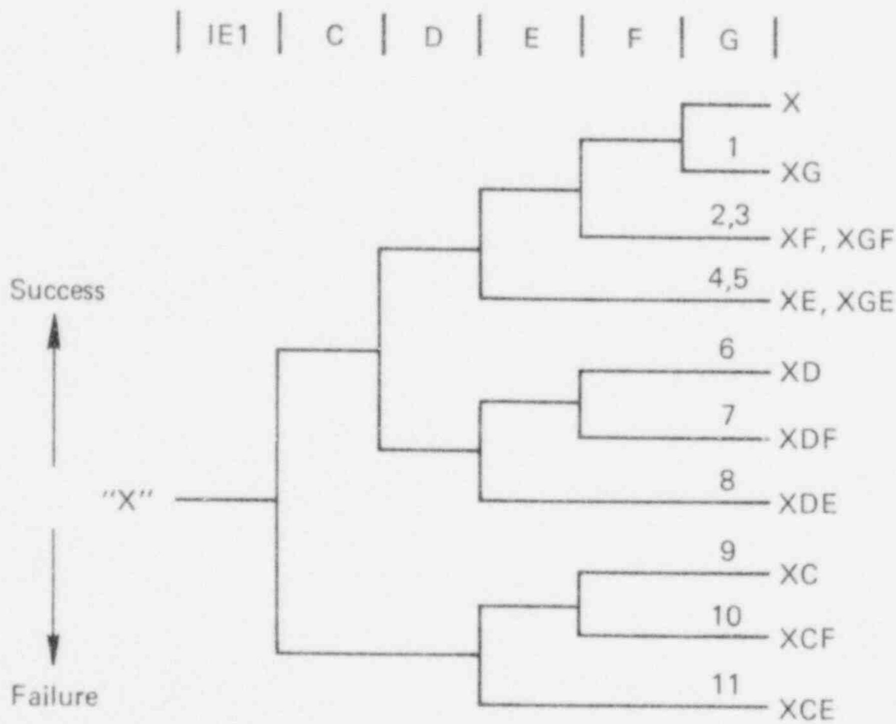


FIG. A.4. Hypothetical initiated event 1 ("X").

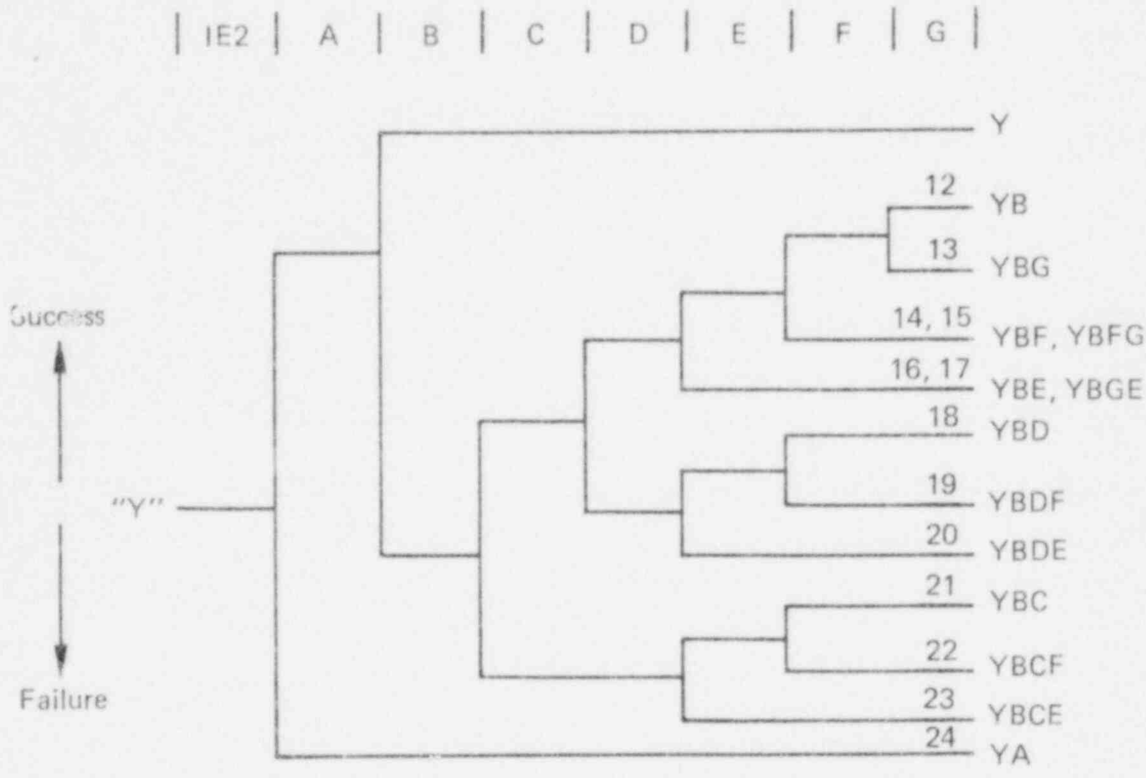


FIG. A.5. Hypothetical initiated event 2 ("Y").

example, the probability of accident sequence 8 of event "X" can be written as

$$P(X \wedge \bar{C} \wedge D \wedge E) \quad , \tag{A.2}$$

where the marginal probabilities of Eq. A.2 are

$P(X)$, the probability of initiated event "X,"
$P(\bar{C})$, the success probability of safety system C,
$P(D)$, the failure probability of safety system D,
$P(E)$, the failure probability of safety system E.

For this discussion, safety system success probabilities are excluded from consideration. This is done in order to simplify the presentation, but has no impact on the generality of the approach. With this in mind, the probability of accident sequence 8 of event "X" is written as

$$P(X \wedge D \wedge E) \quad . \tag{A.3}$$

Event trees are drawn such that dependent events are handled properly. The trees consider the relationship between the functions to be performed, given an initiated event (an example of a function is postaccident radioactivity removal from the containment), and the respective physical systems provided to perform them. Inherent in Eq. A.3 is a further relationship implied by the event trees: the sharing of components between systems.

The general equation for computation of the unconditional probability of an accident sequence can be defined in the following way

$$P(S) = P(S_\ell \wedge I_i \wedge I_j{}^*)$$

$$= P(S_\ell / I_i \wedge I_j{}^*) \cdot P(I_i / I_j{}^*) \cdot P(I_j{}^*) \quad , \tag{A.4}$$

where

$S_\ell / I_i \wedge I_j{}^*$ = accident sequence ℓ, given initiated event i and initiating event j,

I_i = the initiated event upon which sequence S_ℓ is conditioned (e.g., a LOCA initiated by an earthquake),

$P(I_j^*)$ = probability of initiating event j (e.g., an earthquake).

Depending upon how the trees are drawn, the effects of logical intersections at the system level can be minimized. (Because of the nature of the potential loading environments, the responses at which components fail will be correlated across system boundaries. Also, correlations in strengths to failure will exist across system boundaries. These effects can be properly accounted for at the level of the component failure computations.) For the purposes of allocation at the system level, the effect of the logical intersections between systems on the event trees will be neglected. With this further refinement, the probability of accident sequence 8 of event "X" is written as

$$P(X) \cdot P(D) \cdot P(E) \quad . \tag{A.5}$$

In relation to Eq. A.4, "X" in Eq. A-5 is comparable with $P(I_i \wedge I_j^*)$ and $P(D) \cdot P(E)$ is comparable with $P(S_l / I_i \wedge I_j^*)$. Thus Eq. A.5 can be rewritten as

$$P(X') \cdot P(D) \cdot P(E) \quad , \tag{A.6}$$

where

$$P(X') = P(I_i / I_j^*) \cdot P(I_j^*) \quad .$$

A.1.1.3 Containment Failure Modes

The potential for containment failure must be factored into the analysis. The containment of a nuclear power plant is of such construction (e.g., prestressed concrete) that it will likely withstand most conceivable initiating events. However, given an accident sequence that results in a large release of energy to the containment, containment failure could occur. The approach taken in this allocation procedure is to consider containment failure given specified accident sequences:

- A reactor vessel steam explosion is possible if molten fuel becomes well mixed with water in the reactor vessel. The results of such an explosion will be minimal if the vessel does not rupture. If the vessel ruptures and causes the containment to rupture also, large quantities of fission products will immediately be released to the atmosphere.
- Containment leakage can prevent the burning of hydrogen by limiting its accumulation and can prevent containment rupture by overpressurization should postaccident heat removal (PAHR) fail.
- The containment can rupture under the pressure generated by hydrogen burning. The possibility of a hydrogen explosion in the containment is considered to be very low, because the steam generated along with the hydrogen will keep the hydrogen concentration below the critical level.
- Loss of PAHR can cause containment rupture because of overpressurization. For large LOCAs, rupture is considered to be a certainty.

In the event that the above containment failure modes, denoted by α, β, γ, and δ, respectively, have not occurred, core melt through the containment will eventually occur (ε).

Each accident sequence must be paired with each possible containment failure mode, with the resulting conjunction termed a terminal event. The associated terminal event probability is calculated as

$$P(TE) = P(CFM_k/S_i) = P(CFM_k/S_i) \cdot P(S_i) \quad , \tag{A.7}$$

where

$P(CFM_k/S_i)$ = probability of the kth containment failure mode conditional on the ith accident sequence S_i and $k = \alpha, \beta, \gamma, \delta$, and ε,

$P(S_i)$ = unconditional probability as defined in Eq. A.4.

A.1.1.4 System Level Allocation Using Hypothetical Example

The remainder of the allocation procedure at the system level is most easily shown through the continuation of the hypothetical example introduced in ¶A.1.1.2.

For the 24 accident sequences of Figs. A.4 and A.5, Table A.1 indicates (with an "X") each sequence's possible containment failure modes. For example, all five containment failure modes are considered possible for sequences 5, 20, 23, and 24. Table A.2, in turn, assigns each terminal event to one of seven release categories C_m. Accident sequence 2, XF, coupled with containment failure mode α results in the terminal event designated XFα.* (The reason for seven release categories will become apparent later.) As a result of up to five possible containment failure modes for each accident sequence, a total of 69 terminal events result. The 69 terminal events are allocated to the seven release categories as outlined in Table A.3. The parameters $\alpha_1, \alpha_2, \ldots, \alpha_{24}$; $\beta_3, \beta_5, \ldots, \beta_{24}$; $\gamma_5, \gamma_{17}, \ldots, \gamma_{24}$; $\delta_2, \delta_3, \ldots, \delta_{24}$; and $\varepsilon_1, \varepsilon_3, \ldots, \varepsilon_{24}$ are the containment failure modes associated with the 24 sequences. Each release category probability is likely to be dominated by a relatively few terminal events. If the assumption is made that terminal event probabilities decrease rapidly with increasing numbers of systems involved, then the dominant terminal events can be isolated without resort to quantification. (This assumption can be tested by subsequent event tree computations.) For this hypothetical problem, the terminal events marked with asterisks in Table A.3 are considered to dominate the release category probabilities.

Using Eq. A.7, the terminal event XFα of category C_1 can be written

$$P(X')\cdot P(F)\cdot P(\alpha_2) \quad ,$$

where P(X') is defined as in Eq. A.6.

The probability of releasing C_1 curies of ^{131}I can be approximated by summing the dominant terminal event probabilities in category 1, i.e.,

*This terminal event is written as XFα_2 in Table A.3. The subscript is used to indicate that containment failure probabilities are dependent upon the accident sequence involved.

Table A.1. Containment failure modes.

Accident sequence number	Containment failure mode α	β	γ	δ	ϵ
1	X				X
2	X			X	
3	X	X		X	X
4	X			X	
5	X	X	X	X	X
6	X				X
7	X			X	X
8	X				X
9	X				X
10	X			X	X
11	X				X
12					X
13	X				X
14	X			X	
15	X			X	X
16	X			X	
17	X		X	X	X
18	X				X
19	X			X	X
20	X	X	X	X	X
21	X				X
22	X	X		X	X
23	X	X	X	X	X
24	X	X	X	X	X

Table A.2. Release category assignments C_m ($m = 1, ... , 7$).

Accident sequence number	Release category assignment α	β	γ	δ	ϵ
1	3	-	-	-	7
2	1	-	-	3	-
3	3	5	-	7	7
4	1	-	-	3	-
5	1	2	2	2	6
6	3	-	-	-	7
7	3	-	-	7	7
8	3	-	-	-	6
9	3	-	-	-	7
10	3	-	-	7	7
11	3	-	-	-	6
12	-	-	-	-	6
13	3	-	-	-	7
14	1	-	-	3	-
15	3	-	-	7	7
16	1	-	-	3	-
17	1	-	2	2	6
18	1	-	-	-	7
19	1	-	-	7	7
20	1	2	2	2	6
21	1	-	-	-	7
22	1	4	-	7	7
23	1	2	2	6	6
24	1	2	2	2	6

Table A-3. Allocation of terminal events to release categories. The amount of ^{131}I released decreases from left to right.

C_1	C_2	C_3	C_4	C_5	C_6	C_7
$XF\alpha_2$*	$XGE\beta_5$	$XG\alpha_1$*	$YBCF\beta_5$*	$XGF\beta_{22}$*	$XGE\varepsilon_5$	$XG\varepsilon_1$*
$XE\alpha_4$*	$XGE\gamma_5$	$SF\delta_2$*			$XDE\varepsilon_8$	$XGF\delta_3$*
$XGE\alpha_5$	$XGE\delta_5$*	$XGF\alpha_3$			$XCE\varepsilon_{11}$	$XGF\varepsilon_3$
$YBF\alpha_{14}$	$YBGE\gamma_{17}$	$XE\delta_4$*			$YB\varepsilon_{12}$*	$XD\varepsilon_6$*
$YBE\alpha_{16}$	$YBGE\delta_{17}$	$XD\alpha_6$*			$YBGE\varepsilon_{17}$	$XDF\delta_7$
$YBGE\alpha_{17}$	$YBDE\beta_{20}$	$XDF\alpha_7$			$YBDE\varepsilon_{20}$	$XDF\varepsilon_7$
$YBD\alpha_{18}$	$YBDE\gamma_{20}$	$XDE\alpha_8$			$YBCE\delta_{23}$	$XC\varepsilon_9$*
$YBDF\alpha_{19}$	$YBDE\delta_{20}$	$XC\alpha_9$*			$YBCE\varepsilon_{23}$	$XCF\delta_{10}$*
$YBDE\alpha_{20}$	$YBCE\beta_{23}$	$XCF\alpha_{10}$			$YA\varepsilon_{24}$*	$XCF\varepsilon_{10}$
$YBC\alpha_{21}$	$YBCE\gamma_{23}$	$XCE\alpha_{11}$				$YBG\varepsilon_{13}$
$YBCF\alpha_{22}$	$YA\beta_{24}$*	$YBG\alpha_{13}$				$YBGF\delta_{15}$
$YBCE\alpha_{23}$	$YA\gamma_{24}$*	$YBF\delta_{14}$				$YBGF\varepsilon_{15}$
$YA\alpha_{24}$*	$YA\delta_{24}$*	$YBFG\alpha_{15}$				$YBD\varepsilon_{18}$
		$YBE\delta_{16}$				$YBDF\delta_{19}$
						$YBDF\varepsilon_{19}$
						$YBC\varepsilon_{21}$
						$YBCF\delta_{22}$
						$YBCF\varepsilon_{22}$

*Terminal events marked with asterisks are considered to dominate the release category probabilities.

$$P(C_1) = P(X')P(F)P(\alpha_2) + P(X')P(E)P(\alpha_4) + P(Y')P(A)P(\alpha_{24}) \quad . \tag{A.8}$$

There are seven safety systems that must be allocated a limit state probability. The approach taken here is to generate seven simultaneous equations for solution, where the only unknowns are the safety-system allocated probabilities. The expected value of release from all category 1 events can be calculated from the risk profile of Fig. A.1. Assuming category 1 events have the potential for releasing between 10^7 and 10^8 curies, then

$$E(C_1) = P\left(10^7 \leq C_1 < 10^8\right) \times C_{\overline{7,8}} \quad , \tag{A.9}$$

where $C_{\overline{7,8}}$ is the average of 10^7 to 10^8 curies of ^{131}I.

Each sequence of Eq. A.8 assigned to category 1 has the potential for releasing between 10^7 and 10^8 curies of ^{131}I.* The right-hand side of Eq. A.8 can therefore be written in terms of expected value of release

$$P(X')P(F)P(\alpha_2) \times C_{\alpha_2} + p(X')P(E)P(\alpha_4) \times C_{\alpha_4} + P(Y')P(A)P(\alpha_{24}) \times C_{\alpha_{24}} \quad , \tag{A.10}$$

where the C_α are the fractions of core inventory released for each accident sequence and for category 1 releases will take on a value between 10^7 and 10^8 curies of ^{131}I. Setting Eq. A.10 less than or equal to Eq. A.9 results in the following constraints:

---

*The Reactor Safety Study, WASH-1400 (Ref. 1), calculated the cumulative fractions of core inventory released to the atmosphere as a function of time for approximately 38 sequences for the Surrey PWR. This sample of 38 sequences, mostly from the large LOCA tree, was used as the basis for categorizing the remaining sequences from the other trees. An approach such as this could be used here, or the results obtainable from the WASH-1400 study could be used as typical for all light water reactors. This latter approach is probably justifiable, since the aim is not to compute actual risk but to allocate limit state probabilities to components which will result in a plant design capable of meeting some form of risk criterion.

$$P\left(10^7 \le C_1 < 10^8\right) \times C_{\overline{7,8}} \ge P(X')P(F)P(\alpha_2) \times C_{\alpha_2}$$

$$+ P(X')P(E)P(\alpha_4) \times C_{\alpha_4} + P(Y')P(A)P(\alpha_{24}) \times C_{\alpha_{24}} \qquad (A.11)$$

and

$$C_{\overline{7,8}} \doteq \sum_n C\alpha_n/n \quad . \qquad (A.12)$$

Equation A.12 should approach $C_{\overline{7,8}}$ as n increases, i.e., as the number of dominant sequences in category 1 increases.

Since it is likely to be impractical to calculate the values of C_α, a further refinement can be made to Eq. A.11 which results in the following constraint:

$$P\left(10^7 \le C_1 < 10^8\right) \ge P(X')P(F)P(\alpha_2) + P(X')P(E)P(\alpha_4)$$

$$+ P(Y')P(A)P(\alpha_{24}) \quad . \qquad (A.13)$$

The assumption in simplifying Eqs. A.11 to Eqs. A.13 is that $C_{\overline{7,8}} \doteq C_{\alpha_n}$ for n = 2, 4, and 24. In general, this assumption is probably not completely valid, but the results of the allocation are unlikely to be influenced to any great degree if Eq. A.13 is used in place of Eq. A.11.

Referencing Eq. A.13, six further constraints, associated with the remaining six release categories, can be constructed. This results in the following set of constraints

$$P\left(10^7 \le C_1 < 10^8\right) \ge P(X')P(F)P(\alpha_2) + P(X')P(E)P(\alpha_4)$$

$$+ P(Y')P(A)P(\alpha_{24}) \quad , \qquad (A.14a)$$

$$P\left(10^6 \le C_2 < 10^7\right) \ge P(X')P(G)P(E)P(\delta_5) + P(Y')P(A)P(\beta_{24}) \quad ,$$

$$+ P(Y')P(A)P(\gamma_{24}) + P(Y')P(A)P(\delta_{24}) \quad , \qquad (A.14b)$$

$$P\left(10^5 \le C_3 < 10^6\right) \ge P(X')P(G)P(\alpha_1) + P(X')P(E)P(\delta_4)$$

$$+ P(X')P(C)P(\alpha_9) \quad , \qquad \text{(A.14c)}$$

$$P\left(10^4 \le C_4 < 10^5\right) \ge P(Y')P(B)P(C)P(F)P(\beta_5) \quad , \qquad \text{(A.14d)}$$

$$P\left(10^3 \le C_5 < 10^4\right) \ge P(X')P(G)P(F)P(\beta_{22}) \quad , \qquad \text{(A.14e)}$$

$$P\left(10^2 \le C_6 < 10^3\right) \ge P(Y')P(B)P(\varepsilon_{12}) + P(Y')P(A)P(\varepsilon_{24}) \quad , \qquad \text{(A.14f)}$$

$$P\left(10^1 \le C_7 < 10^2\right) \ge P(X')P(G)P(\varepsilon_1) + P(X')P(G)P(E)P(\delta_3)$$

$$+ P(X')P(D)P(\varepsilon_6) + P(X')P(C)P(\varepsilon_9) + P(X')P(C)P(F)P(\delta_{10}) \quad . \qquad \text{(A.14g)}$$

These constraints can be written as follows:

$$A_1 \ge a_{11}X_1 + a_{12}X_2 + a_{13}X_3 \quad , \qquad \text{(A.15a)}$$

$$A_2 \ge a_{21}X_2X_4 + a_{22}X_3 \quad , \qquad \text{(A.15b)}$$

$$A_3 \ge a_{31}X_4 + a_{32}X_2 + a_{33}X_5 \quad , \qquad \text{(A.15c)}$$

$$A_4 \ge a_{41}X_1X_5X_6 \quad , \qquad \text{(A.15d)}$$

$$A_5 \ge a_{51}X_1X_4 \quad , \qquad \text{(A.15e)}$$

$$A_6 \ge a_{61}X_6 + a_{62}X_3 \quad , \qquad \text{(A.15f)}$$

$$A_7 \ge a_{71}X_4 + a_{72}X_2X_4 + a_{73}X_7 + a_{74}X_5 + a_{75}X_1X_5 \quad , \qquad \text{(A.15g)}$$

where the unknowns for solution are the X_i ($i = 1, 2, \ldots, 7$) and the A_m and a_{mn} are constants ($m = 1, 2, \ldots, 7$ and $n = 1, 2, \ldots, 7$).

Two approaches are possible for solution of the system-level allocation X_i. One approach would involve dropping the constraints of Eqs. A.15 and solving the resulting set of simultaneous nonlinear equations in the X_i. The solution of sets of simultaneous nonlinear equations of the above type can be accomplished either by successive approximations or by the method of iteration. A well-known method of successive approximations is that of Newton-Raphson, which has a fairly simple computational form suitable for computer programming. The method of iteration may be applied in cases where it is possible to solve explicitly for each of the variables (e.g., the unknowns of Eqs. A.15 in terms of functions of the variables). This is in fact possible with the set of Eqs. A.15, but the method of iteration may converge very slowly or not at all. It is necessary, therefore, to have a criterion for convergence.

The second approach involves solving Eqs. A.15 as a nonlinear optimization problem. With this approach, a suitable objective function is required. One such objective function, for example, is to minimize the cost of the expected consequences associated with each release category of the risk profile of Fig. A.2. A solution to the nonlinear optimization problem of Eqs. A.15, with a suitable objective function, can be obtained without all seven constraints. This is an advantage over the first approach, where all seven equations are required for a solution. Also, with the second approach a better result is likely, since the problem is constrained to a definite region for solution. Given that a solution to a set of equations such as Eqs. A.15 is fairly easy to obtain, the safety-system limit state probabilities can be allocated. What remains now is to allocate limit state probabilities to the components of each safety system, such that the system limit state probability does not exceed the allocated value. The approach to component allocation is described in the next section.

A.1.2 COMPONENT-LEVEL ALLOCATION METHODOLOGY

A.1.2.1 Fault Trees as a Tool for Component Allocation

The allocation of limit state probabilities to components requires the construction of fault trees which define the possible failure modes of each safety system identified by the event trees. The system failure modes are defined in terms of cut-sets which consist of intersections of the basic events of the fault trees. The basic events of the fault trees include such events as component failure to which limit state probabilities must be allocated.

To illustrate the use of fault trees for the component-level allocation procedure, Fig. A.6 is assumed to represent the fault tree for system A, which was called out in the event tree (Fig. A.5). Load-related failures are denoted X_i^F and failures due to other causes are denoted X_j^R. These failure causes will subsequently be referred to as fragility related and random related, respectively. The Boolean expression describing the set of system failure modes is

$$A = X_1^R \wedge X_2^R \cup X_1^R \wedge X_2^F \cup X_1^R \wedge X_3^R \cup X_1^R \wedge X_3^F \cup X_1^F \wedge X_2^R \cup X_1^F \wedge X_2^F \cup X_1^F \wedge X_3^R \cup X_1^F \wedge X_3^F \ . \tag{A.16}$$

The corresponding probability expression for system A is obtained from the expansion of Eq. A.16 in the manner outlined by the following

$$P(A) = \sum_{i=1}^{n} P(A_i) - \sum_{i=2}^{n} \sum_{j=1}^{i-1} P(A_i \wedge A_j) + \sum_{i=3}^{n} \sum_{j=2}^{i-1} \sum_{k=1}^{j-1} P(A_i \wedge A_j \wedge A_k)$$

$$- \ . \ . \ . + (-1)^{n-1} \prod_{i=1}^{n} P(\wedge A_i) \ , \tag{A.17}$$

where $n = 8$ and $A_1 = X^F \wedge X^F$, etc. Therefore,

$$P(A) = P\left(X_1^R \wedge X_2^R\right) + P\left(X_1^R \wedge X_2^F\right) + P\left(X_1^R \wedge X_3^R\right) + P\left(X_1^R \wedge X_3^F\right) + P\left(X_1^F \wedge X_2^R\right)$$

$$+ P\left(X_1^F \wedge X_2^F\right) + P\left(X_1^F \wedge X_3^R\right) + P\left(X_1^F \wedge X_3^F\right) - P\left(X_1^R \wedge X_2^R \wedge X_3^R\right)$$

$$- P\left(X_1^R \wedge X_2^R \wedge X_3^F\right) - P\left(X_1^R \wedge X_2^F \wedge X_3^R\right) - P\left(X_1^R \wedge X_2^F \wedge X_3^F\right) - P\left(X_1^F \wedge X_2^R \wedge X_3^R\right)$$

$$- P\left(X_1^F \wedge X_2^R \wedge X_3^F\right) - P\left(X_1^F \wedge X_2^F \wedge X_3^R\right) - P\left(X_1^F \wedge X_2^F \wedge X_3^F\right) \ . \tag{A.18}$$

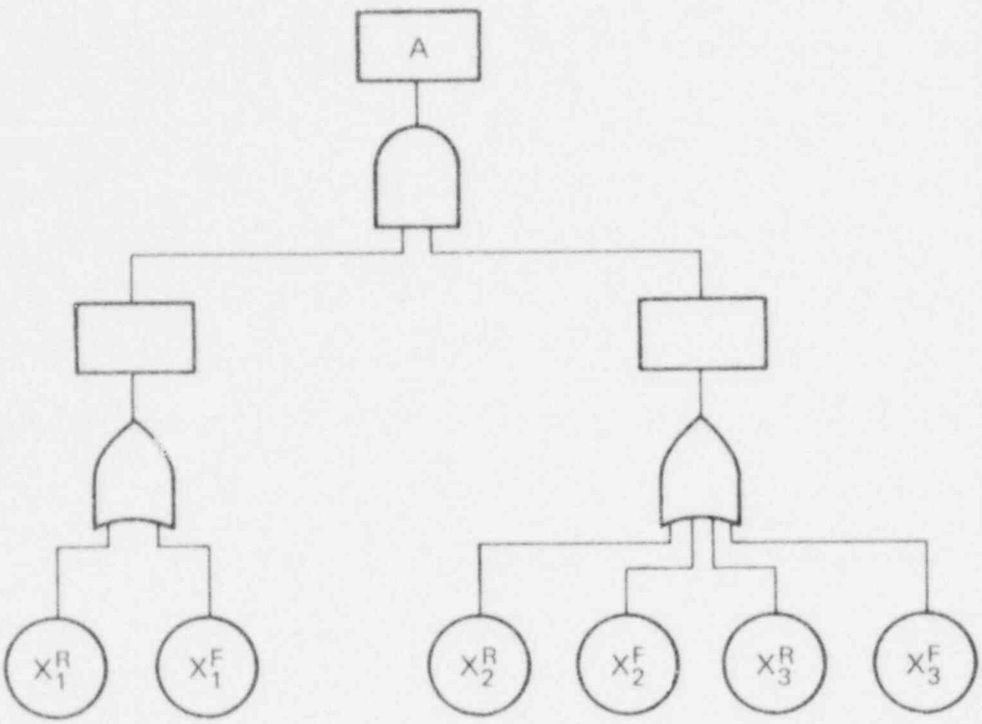


FIG. A.6. Illustrative fault tree for safety system A.

The occurrence of a fragility-related failure for a specific component precludes the possibility that it subsequently could fail randomly, and vice versa; i.e., fragility-related failures and random failures are mutually exclusive for the same basic event, and this is reflected in the derivation of Eq. A.18.

Equation A.18 can be simplified by assuming that (a) fragility-related failures occur independently of random-related failures and that (b) all marginal random-related failure probabilities are small on a plant-year basis. Therefore, P(A) can be written

$$
\begin{aligned}
P(A) = {} & P\left(X_1^R\right)P\left(X_2^R\right)\left[1 - P\left(X_3^R\right)\right] + P\left(X_1^R\right)P\left(X_2^F\right)\left[1 - P\left(X_3^R\right)\right] \\
& + P\left(X_1^R\right)P\left(X_3^R\right) + P\left(X_1^R\right)P\left(X_3^F\right)\left[1 - P\left(X_2^R\right)\right] \\
& + P\left(X_1^F\right)P\left(X_2^R\right)\left[1 - P\left(X_3^F\right)\right] + P\left(X_1^F\ X_2^F\right)\left[1 - P\left(X_3^R\right)\right] \\
& + P\left(X_1^F\right)P\left(X_3^R\right) + P\left(X_1^F\ X_3^F\right)\left[1 - P\left(X_2^R\right)\right] \\
& - P\left(X_1^R\right)P\left(X_2^F\ X_3^F\right) - P\left(X_1^F\ X_2^F\ X_3^F\right) \quad .
\end{aligned}
\tag{A.19}
$$

The above two assumptions then result in the following:

$$
\begin{aligned}
P(A) \doteq {} & P\left(X_1^R\right)P\left(X_2^R\right) + P\left(X_1^R\right)P\left(X_2^F\right) + P\left(X_1^R\right)P\left(X_3^R\right) + P\left(X_1^R\right)P\left(X_3^F\right) \\
& + P\left(X_1^F\right)P\left(X_2^R\right) + P\left(X_1^F \wedge X_2^F\right) + P\left(X_1^F\right)P\left(X_3^R\right) + P\left(X_1^F \wedge X_3^F\right) \\
& - P\left(X_1^R\right)P\left(X_2^F \wedge X_3^F\right) - P\left(X_1^F \wedge X_2^F \wedge X_3^F\right) \quad .
\end{aligned}
\tag{A.20}
$$

Equation A.20 differs from Eq. A.16 only in its last two terms, which are subtractive. The effect of the last two higher-order terms of Eq. A.20 is dependent on the magnitude of the marginal probabilities of the basic events. If the marginal probabilities of X_1^R, X_1^F, X_2^F, and X_3^F are quite small (of the order ≤ 0.1), then their effect on the value of P(A) will be small. In fact, an upper bound on the system limit state probability can be obtained through the use of Eq. A.16.

The use of equations such as Eq. A.16 to obtain an upper bound on the system limit state probability has one very appealing advantage--the expansion to probability form is avoided. The general expansion of Eq. A.17 results in 2^{n-1} terms in the probability expression. For large systems with many basic events, this approach becomes prohibitive, even if independence between all basic events is assumed and all logical redundancies have been removed from the fault tree structure. (If logical redundancies are not present and independence between the basic events can be assumed, the system failure probability can be calculated directly from the Boolean model through numerical substitution. This can be done with relative ease on a computer.)

For the type of problem considered here, independence between fragility-related events cannot be assumed. Component local responses (in a specified loading environment) are likely to be correlated, as are component strengths. For the purposes of allocation at the component level, therefore, the use of equations such as Eq. A.16 is recommended. This will result in slightly conservative estimates for the allocated values (i.e., it will slightly overestimate the required allocated values). The degree of conservatism in the calculated upper bound for the system limit state probability can be estimated through the calculation of what is called Hunter's bound.[3]

Hunter's bound maximizes the second term of the following:

$$P(\cup A_i) \leq \sum P(A_i) - \sum_{\tau} P(A_i \wedge A_j) \quad , \tag{A.21}$$

where τ is some spanning tree of the nodes A_i in the set T of such trees and the intersection $A_i \wedge A_j$ are the branches joining two of the nodes. The computation of Hunter's bound requires finding the tree $\tau \in T$ that maximizes the second term of Eq. A.21, yielding the lowest upper bound of the form

$$P(\cup A_i) \leq \sum P(A_i) - \max_{\tau \in T} \sum_{\tau} P(A_i \wedge A_j) \quad . \tag{A.22}$$

A.1.2.2 Component-Level Allocation Procedural Steps

The discussion of the allocation at the component level will be related to Fig. A.7, which outlines the procedural steps in flow diagram form. Various issues and assumptions related to the procedure will be probed as the discussion proceeds. It is important to note that the allocation procedure merely sets constraints on the component limit state probabilities for future detailed design.

With reference to Fig. A.7, the identification of the fault tree basic events in step 3 determines the amount of input data required to perform steps 4, 5, and 6. It is suggested that means and standard deviations of response data be sought from that available, based on current designs. For example, current component designs will specify the maximum expected loadings over the lives of components. It will likely be possible to categorize components and to obtain the required data for each category only, rather than for every basic event identified by the fault trees. Fragility data may be harder to obtain, but a start can be made with that available from the SSMRP. Some discussion was provided in Sec. 4.4 in regard to obtaining correlation data and will not be elaborated on here.

It would be possible to allocate a limit state probability to a component for each of its possible failure modes as related to each different combined loading case. However, this is not a practical approach to allocation in terms of the amount of quantification and would necessitate a two-stage design procedure. A limiting-case approach is proposed here in order to reduce the amount of computation required for the allocation. By definition, given that the limiting cases are satisfied, all other cases will be satisfied. This limiting-case approach will lead to a single limit state probability allocation for each component for input into the detailed probabilistic design process. If, subsequently, several potential failure modes are identified for a given component, then each of their occurrence probabilities (as calculable in the detailed design phase) must not exceed the limiting-case allocated value.

Because of the nature of potential loading environments, local responses, as measured at components, could be correlated. Also, because many components are fabricated in the same way or come from the same manufacturer, their strengths to failure could also be correlated. The allocation procedure, as

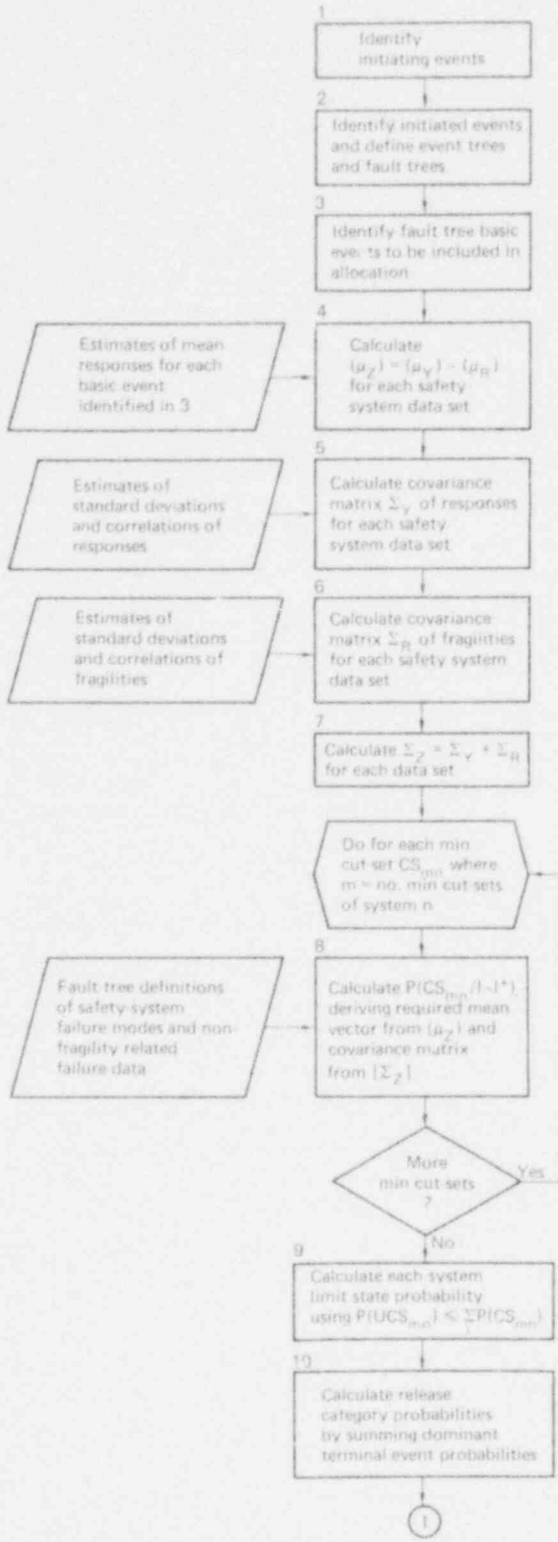
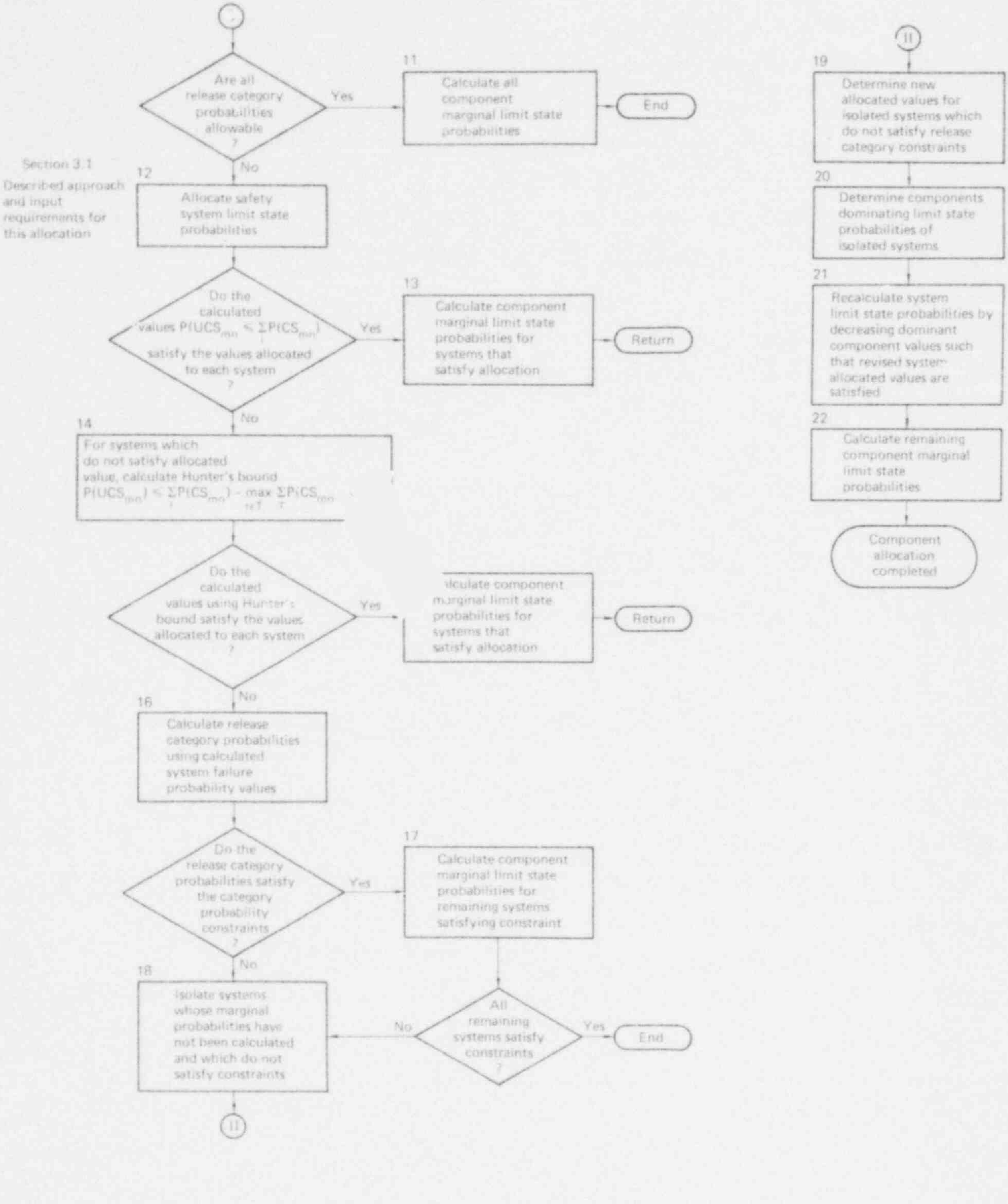


FIG. A.7. Component allocation procedure.



Are all release category probabilities allowable ?
Yes
No
11
Calculate all component marginal limit state probabilities
End
Section 3.1
Described approach and input requirements for this allocation
12
Allocate safety system limit state probabilities
Do the calculated values P(UCS$_{mn}$) ≤ ΣP(CS$_{mn}$) satisfy the values allocated to each system ?
13
Calculate component marginal limit state probabilities for systems that satisfy allocation
Return
14
For systems which do not satisfy allocated value, calculate Hunter's bound
Do the calculated values using Hunter's bound satisfy the values allocated to each system ?
marginal limit state probabilities for systems that satisfy allocation
Return
16
Calculate release category probabilities using calculated system failure probability values
Do the release category probabilities satisfy the category probability constraints ?
17
Calculate component marginal limit state probabilities for remaining systems satisfying constraint
18
Isolate systems whose marginal probabilities have not been calculated and which do not satisfy constraints
All remaining systems satisfy constraints ?
End
II
19
Determine new allocated values for isolated systems which do not satisfy release category constraints
20
Determine components dominating limit state probabilities of isolated systems
21
Recalculate system limit state probabilities by decreasing dominant component values such that revised system allocated values are satisfied
22
Calculate remaining component marginal limit state probabilities
Component allocation completed

FIG. A.7. (Cont.)

previously pointed out in Sec. 4.4, must therefore take account of the correlated nature of failure. Details of the approach to computation of limit state probability at the component level, in a correlated environment, are contained in Appendix B. The procedure essentially requires the use of normal or lognormal distributions to characterize the uncertainties in component responses and in component fragilities. Given this assumption of normality, the approach correctly handles the correlated nature of failure in a combined loading environment.

The need for the computation of steps 4, 5, 6, and 7 is explained in detail in Appendix B. For the purposes of explaining the allocation approach, it is sufficient to say that these steps are required in order to compute the fault tree cut-set probabilities.

The covariance matrices of component response (local response to combined loadings) and of component fragilities are calculated in steps 5 and 6. The suggested approach is to calculate a response and fragility covariance matrix for each safety system, as called out by the event trees. Strictly speaking, separate covariance matrices should not be calculated for each set of safety system responses and fragilities, since the underlying assumption of this approach is that in a common loading environment responses and fragilities across systems are uncorrelated. This loss of sensitivity in terms of correlated failure at the system level is not complete, since the event trees will include both functional and operational dependencies between systems. In any event the assumption of zero correlation among responses and fragilities across systems is likely to have little effect on the allocated marginal limit state probabilities of components. Furthermore, the structuring of the allocation procedure in the manner set forth here simplifies the computations and provides a suitable approach towards mechanization of the computations.

The calculation of safety-system limit state probabilities is accomplished in steps 8 and 9. In order to compute the limit state probability of each safety system, the relevant minimal cut-set expressions must be defined. These cut-set expressions can be described collectively as the set of system "failure modes." Equation A.16 defines the set of failure modes of system A, which will be referenced in order to explain subsequent steps of the allocation procedure.

The computational algorithm described in Appendix B will enable the computation of cut-set probabilities, with proper accounting of dependencies between component responses and between component fragilities (accepting the assumptions of normality or lognormality describing the distributions of uncertainties). Step 8 indicates the calculation of cut-set m of safety system n, given that initiated event i and initiating event j have occurred. (This notation may appear somewhat cumbersome, but it is important to point out that the set of possible failure modes for a system is dependent upon the initiated event, which in turn is dependent upon the initiating event.)

An upper bound on each system limit state probability is obtained in step 9. This is equivalent to the use of Eq. A.16 to obtain the upper bound for system A.

Step 10 requires the computation of release category probabilities by summing the dominant terminal events assigned to each release category. (Refer to ¶A.1.1.4 for a discussion of release categories and dominant terminal events.) If the calculated release category probabilities satisfy the plant risk profile, then the component marginal limit state probabilities are calculated in step 11. These calculated values are the "allocated" values for detailed design. (It will be noted that up to and including step 11 no actual allocation has taken place. The calculated values satisfy the risk criterion.)

If the release category probabilities are not satisfied in step 10, then the system-level allocation as outlined in Sec. A.1.1 must proceed. This is indicated by step 12.

Marginal limit state probabilities are calculated in step 13 for components of systems whose calculated upper-bound values satisfy the system-level allocated value. The computed component marginal failure probabilities are the required allocations for detailed design.

Since the upper bound calculated in step 9 is a conservative estimate of the safety-system limit state probability, step 14 is included. The computation of Hunter's bound can be done for those systems where the upper bound calculated in step 9 exceeds the system-level allocated value. The computation of Hunter's bound, as indicated by Eq. A.22, requires the inclusion of some subtractive cross-product terms in the expanded Boolean form for the safety-system limit state probability. Equation A.20 is the exact result (given the acceptability of the relevant assumptions) for the limit state probability of system A. (For system A the exact result will likely correspond to Hunter's bound.) If the better estimates calculable through the use of Hunter's bound satisfy the system-level allocated values, then the procedure is completed in step 15. It should be noted that the intent is to compute Hunter's bound only for those systems which do not satisfy the system-level allocation, as indicated by the conservative estimates made in step 9.

The allocation procedure will be incomplete after step 14 if the calculated limit state probability for one or more systems still does not satisfy its allocated value. However, the calculated safety system probabilities may in total satisfy the set of release category constraints. Using Eq. A.14 as an analogy, it can be seen that, if these constraints are satisfied with the system failure probabilities computed so far (some conservative estimates and some Hunter's bound estimates), then the allocation need proceed no further than step 7.

Those systems which still do not allow compliance with the release category constraints are isolated in step 18. It will be possible to relax somewhat the original system-level allocated values for those systems which up to step 18 still do not allow complete satisfaction of the release category constraints. This is done in step 19, where the only unknowns in the solution of Eq. A.14, for example, are the new probability values to be allocated to those systems which do not satisfy their original allocated values.

Armed with these new system-level allocated values of the noncompliant systems, the allocation proceeds to step 20. It is likely that only a subset of the set of all basic events (components) identified by the fault tree for a system will dominate the system's limit state probability. Step 20 seeks to identify these dominant components of the isolated systems and thus effectively reduce the computations required in step 21.

Step 21 will be explained in terms analogous to Eq. A.16 for hypothetical system A. Assume that this system has been isolated as the only noncompliant one of the seven systems of the hypothetical example described in Sec. A.1.1. An upper bound on the limit state probability for system A is obtained by the following:

$$P(A) = P\left(X_1^R\right)\cdot P\left(X_2^R\right) + P\left(X_1^R\right)\cdot P\left(X_2^F\right) + P\left(X_1^R\right)\cdot P\left(X_3^R\right) + P\left(X_1^F\right)\cdot P\left(X_2^R\right)$$

$$+ P\left(X_1^F \wedge X_2^F\right) + P\left(X_1^F\right)\cdot P\left(X_3^R\right) + P\left(X_1^F \wedge X_3^F\right) \quad . \qquad (A.23)$$

Since the allocation at the component level is concerned only with load-related failures, the probabilities associated with the random-related basic events (X_1^R) can be considered as given constant values. Equation A.23 can now be written

$$P(A) = C_1 + C_2P\left(X_2^F\right) + C_3P\left(X_1^F\right) + P\left(X_1^F \wedge X_1^F\right) + P\left(X_1^F \wedge X_3^F\right) \quad . \tag{A.24}$$

Furthermore, if X_2^F and X_3^F are alone considered to dominate the analysis, then the computed marginal limit state probability for X_1^F can be considered as invariant in subsequent computations aimed at satisfying the new allocated value for system A obtained in step 19. Equation A.24 can now be written

$$P(A) = C_4 + C_2P\left(X_2^F\right) + P\left(X_1^F \wedge X_2^F\right) + P\left(X_1^F \wedge X_3^F\right) \quad . \tag{A.25}$$

The procedure now requires calculation of the marginal limit state probabilities of the basic events X_2 and X_3 such that the system-level allocated value is not exceeded. The only way the designer can reduce the marginal limit state probabilities of the basic events X_2 and X_3 is by increasing their respective strengths (fragilities). If Eq. A.25 is rewritten as

$$P(A) \geq C_4 + C_2P\left(K_2X_2^F\right) + P\left(X_1^F \wedge K_2X_2^F\right) + P\left(X_1^F \wedge K_3X_3^F\right) \quad , \tag{A.26}$$

then the K factors represent the amount by which the strengths of components X_2 and X_3 must be increased in order to satisfy the system-level allocated value. No unique solution exists for K_2 and K_3, but assumptions such as $K_2 = K_3$ can be made in order to find an acceptable solution. The choice of relationship between the K values could be qualitatively based on such parameters as importance, cost, complexity, etc.

APPENDIX B: COMPUTATION OF COMPONENT LIMIT STATE PROBABILITIES

The analytical component probability computations, described mathematically in this appendix, are described with consideration of the statistical correlations between component strengths and the correlations between component local responses to the effect of a combined loading environment. This is accomplished by using the multivariate normal (or lognormal) distribution.

Let the peak measured response at the point of interest in the structure or component be designated by R, and the capacity of the structure or component be designated by F.* Then failure occurs when either (Fig. A.8)

$$Y > R$$

or

$$\frac{Y}{R} > 1 \tag{B.1}$$

The choice of $Y > R$ or $Y/R > 1$ depends upon the assumption for the probability distribution of Y and R. If both Y and R are normally distributed, $Y > R$ is appropriate. If both are lognormally distributed, then $\ln Y > \ln R$ $(Y/R > 1)$ is appropriate. The lognormal distribution is more appropriate to use because of its properties $(0 < Y < \infty,\ 0 < R < \infty)$ and is used for the remainder of this development.

For a single variate, let $Z = Y/R$. If $Y > R$, then $Z > 1$ and $0 < \ln Z < \infty$. Assuming independence between $\ln Y$ and $\ln R$, $\mu_{\ln Z} = \mu_{\ln Y} - \mu_{\ln R}$ and $\sigma^2_{\ln Z} = \sigma^2_{\ln Y} + \sigma^2_{\ln R}$.

For the multivariate case, covariance matrices must be developed for $\ln Y$ and $\ln R$, where $\{\ln Y\}$ and $\{\ln R\}$ are vectors of values representing corresponding peak response and capacities at various points within the

---

*Resistance or capacity is sometimes referred to as fragility. The presentation of fragility is usually in the form of a cumulative probability distribution of failure as a function of measured local response. If a probability density function is used to describe variability in capacity, then its integration is equivalent to the fragility curve.

system. The covariance matrices are arrays containing all of the variances and covariances of the vectors. Using the lognormal representation for responses we have

$$\left[\sum_{\ln Y}\right] = \begin{bmatrix} \sigma^2_{\ln y_1} & \sigma_{\ln y_1 \ln y_2} & \sigma_{\ln y_1 \ln y_3} & \cdot \\ \cdot & \sigma^2_{\ln y_2} & \sigma_{\ln y_2 \ln y_3} & \cdot \\ \text{symmetric} & \cdot & \sigma^2_{\ln y_3} & \cdot \\ & & \cdot & \cdot \end{bmatrix} , \qquad (B.2)$$

where

$$\sigma^2_{\ln y_i} = \int_{-\infty}^{\infty} \left(\ln y_i - \mu_{\ln y_i}\right)^2 f(\ln y_i)\, d(\ln y_i) \quad ,$$

$$\mu_{\ln y_i} = \int_{-\infty}^{\infty} \ln y_i\, f(\ln y_i)\, d(\ln y_i) \quad ,$$

$$\sigma_{\ln y_i \ln y_j} = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left(\ln y_i - \mu_{\ln y_i}\right)\left(\ln y_j - \mu_{\ln y_j}\right)$$

$$\cdot\, f(\ln y_i, \ln y_j)\, d(\ln y_i)\, d(\ln y_j) \quad .$$

The functions $f(\ln y_i)$ and $f(\ln y_i, \ln y_j)$ are univariate and bivariate normal distributions of the logarithms of y_i and y_j.

The values in Eq. B.2 can be developed by a joint statistical analysis of the peak responses at each location. A similar covariance matrix exists for the capacity of the component or structure at the response points. Covariance elements (off-diagonal terms) in this matrix frequently will be zero, except in the cases where, for example, they represent correlation between identical components from the same manufacturer.

Following the development for a single variate, the vector ln Z can be developed, such that

$$\{\mu_{\ln Z}\} = \{\mu_{\ln Y}\} - \{\mu_{\ln R}\} \qquad (B.3)$$

and

$$\left[\Sigma_{\ln Z}\right] = \left[\Sigma_{\ln Y}\right] + \left[\Sigma_{\ln R}\right] \quad . \tag{B.4}$$

At this point we have the complete description of a multivariate lognormal distribution, capable of being used to compute the marginal or joint probability of failure of any one or of a group of components within the system. Thus, this description can be used to compute properly the joint probabilities of failure defined by the minimal cut-sets resulting from the fault tree definitions of the system. The first step in this procedure is to form marginal distributions represented by the elements of the cut-sets. For example, consider the computation of $P(\ln Z_i > 0)\,(\ln Z_j > 0)$. The covariance matrix for the marginal distribution is

$$\begin{array}{cc}
\begin{array}{cccccc} \phantom{\sigma^2_{\ln z_1}} & & \text{column } i & & \text{column } j & \end{array} & \\
\left[\begin{array}{cccccc}
\sigma^2_{\ln z_1} & \cdot & \cdot & \cdot & \cdot & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
\cdot & \cdot & \sigma^2_{\ln z_i} & \cdot & \sigma_{\ln z_i \ln z_j} & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
\cdot & \cdot & \sigma_{\ln z_i \ln z_j} & \cdot & \sigma^2_{\ln z_j} & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot
\end{array}\right] &
\begin{array}{l} \\ \\ \text{row } i \\ \\ \text{row } j \\ \\ \end{array}
\end{array}$$

$$\rightarrow \begin{bmatrix} \sigma^2_{\ln z_i} & \sigma_{\ln z_i \ln z_j} \\ \sigma_{\ln z_i \ln z_j} & \sigma^2_{\ln z_j} \end{bmatrix} = \left[\Sigma_{ij}\right] \quad . \tag{B.5}$$

The joint probability is obtained from the integration

$$P\,(\ln Z_i>0)\,(\ln Z_j>0) = \int_0^{\infty}\int_0^{\infty} f(\ln z_i,\, \ln z_j)\; d(\ln z_i)\; d(\ln z_j)$$

$$= \frac{1}{\left|\sum_{ij}\right|^{1/2}(2\pi)} \int_0^{\infty}\int_0^{\infty} \exp\left[-\frac{1}{2}\begin{Bmatrix}\ln z_i - \mu_{\ln z_i}\\ \\ \ln z_j - \mu_{\ln z_j}\end{Bmatrix}^T\right.$$

$$\left.\cdot\left[\sum_{ij}\right]^{-1}\begin{Bmatrix}\ln z_i - \mu_{\ln z_i}\\ \\ \ln z_j - \mu_{\ln z_i}\end{Bmatrix}\right] d(\ln z_i)\; d(\ln z_j)\quad . \tag{B.6}$$

The most significant aspect of the above discussion is that joint, as well as univariate, limit state probabilities can be computed. This correctly handles the problems of correlated failure.

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This second interim report on load combination methodology development has focused on two objectives: methodology development for combining generic dynamic responses, and the application of the load combination methodology to nuclear power plant components. Different component designs have been analyzed in terms of the methodology. Two examples are provided. One is a simple, highly idealized example that illustrates the essential aspects of developing probabilistic design criteria for multiple loadings. The second, more realistic example is a segment of an essential service water line subjected to internal pressure, dead weight, earthquake, an hydraulic transient, and thermal expansion.

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