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Measures of Risk Importance And Their Applications

Prepared by W. E. Vesely, T. C. Davis, R. S. Denning, N. Saltos

Battelle Columbus Laboratories

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Prepared by
W. E. Vesely, T. C. Davis, R. S. Denning, N. Saltos

Battelle Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

Prepared for
Division of Risk Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

LIST OF TABLES (CONTINUED)

LIST OF TABLES
(CONTINUED)

EXECUTIVE SUMMARY

The objectives of this work are to evaluate the importance of the containment and the different safety functions as assessed in probabilistic risk analyses. To accomplish this objective, risk importance measures are defined to evaluate a feature's importance in further reducing the risk and its importance in maintaining the present risk level. One defined importance measure, called the feature's risk reduction worth, is useful for prioritizing feature improvements which can most reduce the risk. The other defined importance, called the feature's risk achievement worth, is useful for prioritizing features which are most important in reliability assurance and maintenance activities.

Any type of feature can be evaluated for its risk reduction worth and its risk achievement worth; safety functions, safety systems, components, surveillance tests, human activities, mitigation functions, and containments can all be quantified as to their worths. Evaluating the worth in a structured manner from general safety function worths to detailed component, test, and human activity worths allows one to successively focus on the important items. The worths also provide important information for cost-benefit and value-impact analysis, as the report describes. The limitations, assumptions and uncertainties of Probabilistic Risk Analysis should be considered when making risk based decisions. Sensitivity analysis can be used to identify the importance of assumptions and areas where more in-depth analysis is needed. Since much of the information contained in the risk importance measures is relative, much of the analyses can be made robust to risk analysis uncertainties.

The defined risk worth measures are applied to the risk analyses performed in the Reactor Safety Study Methodology Applications Program (RSSMAP). Four plants were analyzed in RSSMAP: Oconee, Grand Gulf, Calvert Cliffs, and Sequoyah, and the risk worths are applied to each of the plant's risk analysis. Safety functions, safety systems, containment, and certain components and human activities are specifically evaluated for their worths.

A summary of the findings of the RSSMAP evaluations for the systems at each of the four plants is presented on Figures i, ii, iii, and iv which are extracted from the body of the report. The figures show the risk achievement ratios and the risk reduction ratios on the same graph with core melt frequency as the risk measure. The risk achievement ratios are the factor by which core melt frequency would increase if the system did not exist or were not operable. The risk reduction worths are graphed below the dividing line and indicate the maximum factor by which core melt frequency could be reduced at the plant by improving the system. The human action identified by RSSMAP which had the largest risk achievement worth is also shown for each of the four plants.

The risk achievement worths identified the features which contribute most to achieving the present risk level and toward which reliability assurance activities should be directed. What stands out most is the very high worths of certain systems and the differences of feature worths among plants. The high importance of support systems such as service water is highlighted by the figures. The importance of certain front line systems such as the reactor protection system is also emphasized by their large risk achievement worths.

As observed from the figures for most systems and human actions the core melt frequency reduction potentials are small, less than a factor of 2. A core melt frequency reduction potential of greater than a factor of 5 was calculated for only one system at one plant (the auxiliary feed system at Calvert Cliffs).

In general, the high risk achievement worths and relatively low risk reduction worths indicate that attention should not be diverted from maintaining and assuring the present reliabilities when efforts are undertaken to reduce risk.

From the importance evaluations performed, human actions as modeled by RSSMAP are found to be near optimal. Improvement of the associated human reliability would not reduce risk significantly whereas degraded human performance could markedly increase risk.

The risk worth measures developed in this report were also applied to the containments of each of the RSSMAP plants. The risk measures for the containment worths were acute fatalities and dose rather than core melt frequency.

The containment worth results are shown in Table i, which has been extracted from the body of the report. The risk achievement ratios indicate the containment presently reduces dose by a factor of about 3 and reduces early fatalities by a factor of 10. The risk reduction ratios indicate that acute fatalities could be reduced to essentially zero (giving a risk reduction ratio of infinity) for those plants not having the V sequence (releases which bypass containment). With the V sequence acute fatalities could at most be reduced by a factor of ~10. For those plants without V, manrem could be reduced by a factor of ~1000 if containment were optimized; for plants with V, a factor of ~10 is the most that dose can be reduced.

In order to further investigate the importance of containment, one of the plants was analyzed assuming different containment designs could be placed on one system design. The risk worths were then calculated for each containment design. The results showed the containment design could have an order of magnitude or more importance to risk estimates. Additional sensitivity studies were performed and are described in the report.

FIGURE i. RISK WORTH RATIOS FOR SEQUOYAH SAFETY SYSTEMS WITH REGARD TO CORE MELT FREQUENCY

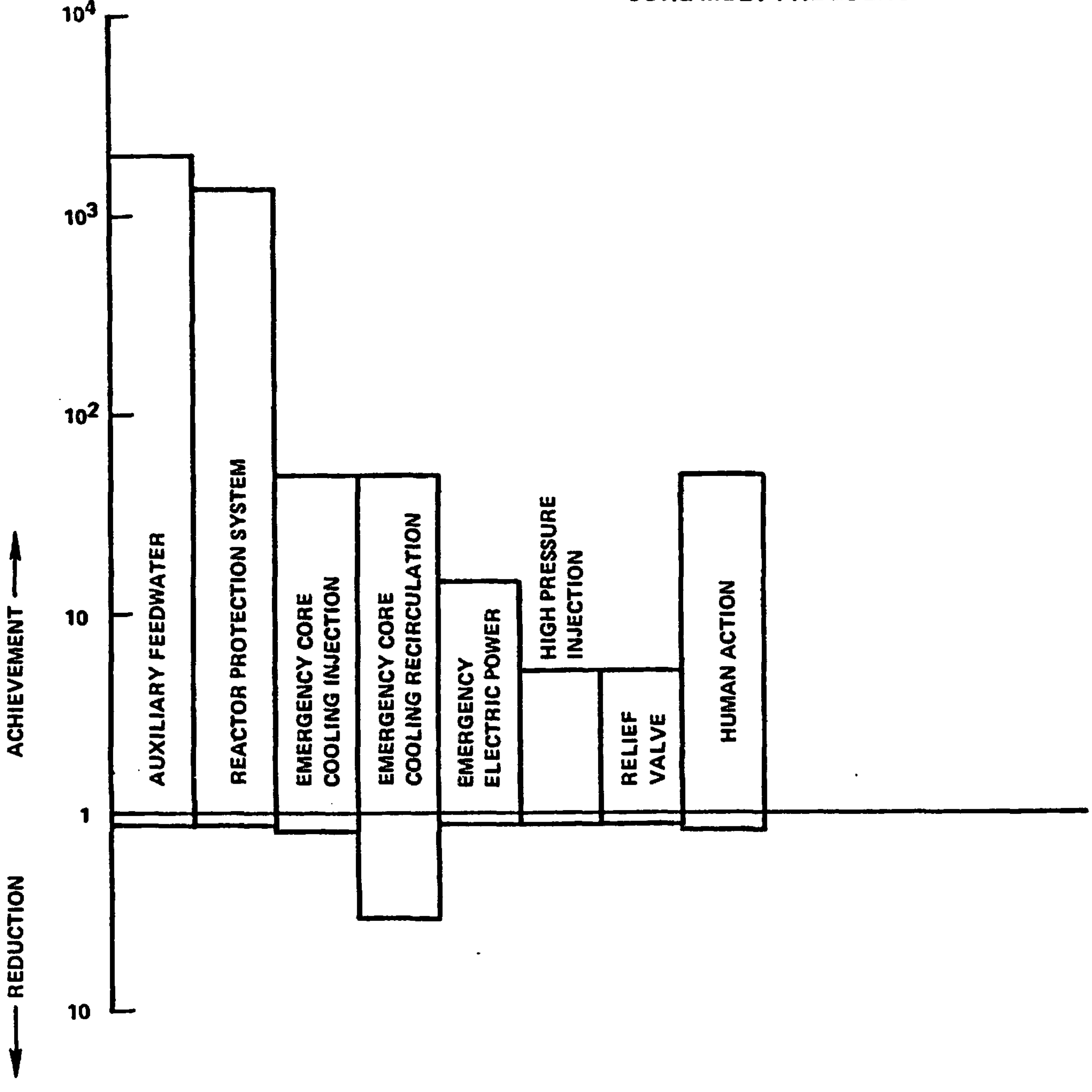


FIGURE ii. RISK WORTH RATIOS FOR OCONEE SAFETY SYSTEMS WITH REGARD TO CORE MELT FREQUENCY

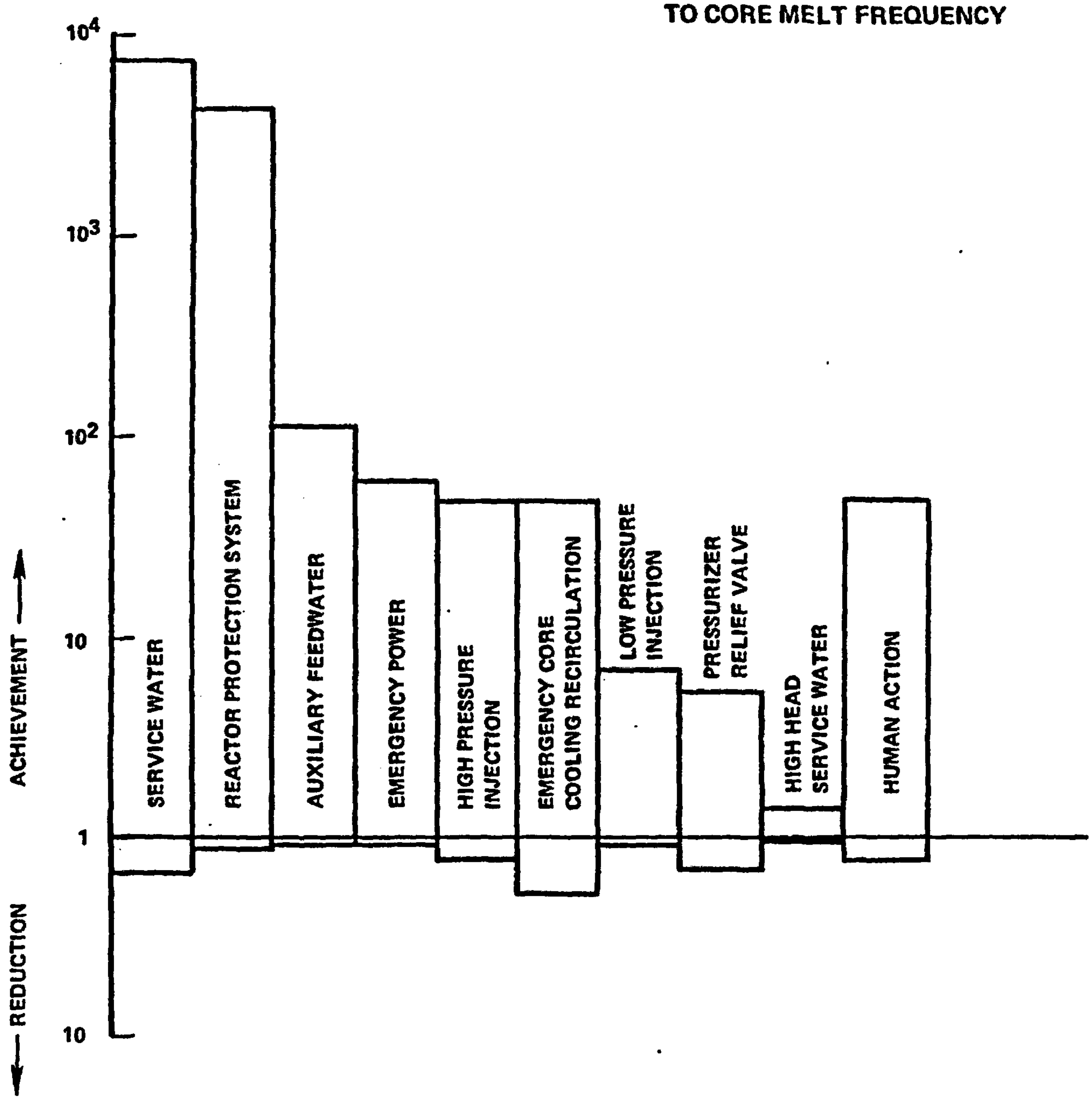


FIGURE iii. RISK WORTH RATIOS FOR CALVERT CLIFFS SAFETY SYSTEMS WITH REGARD TO CORE MELT FREQUENCY

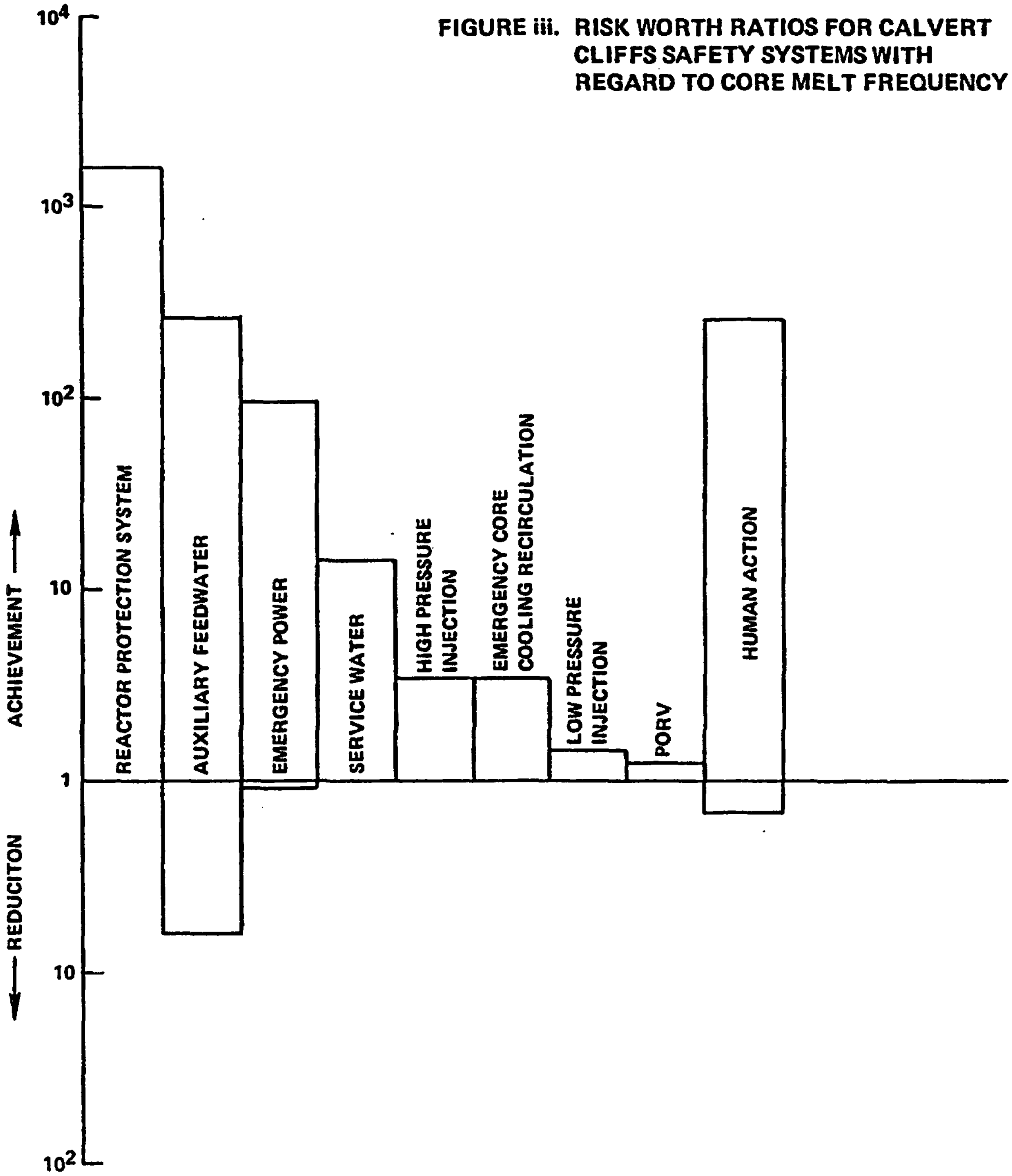


FIGURE iv. RISK WORTH RATIOS FOR GRAND GULF SAFETY SYSTEMS WITH REGARD TO CORE MELT FREQUENCY

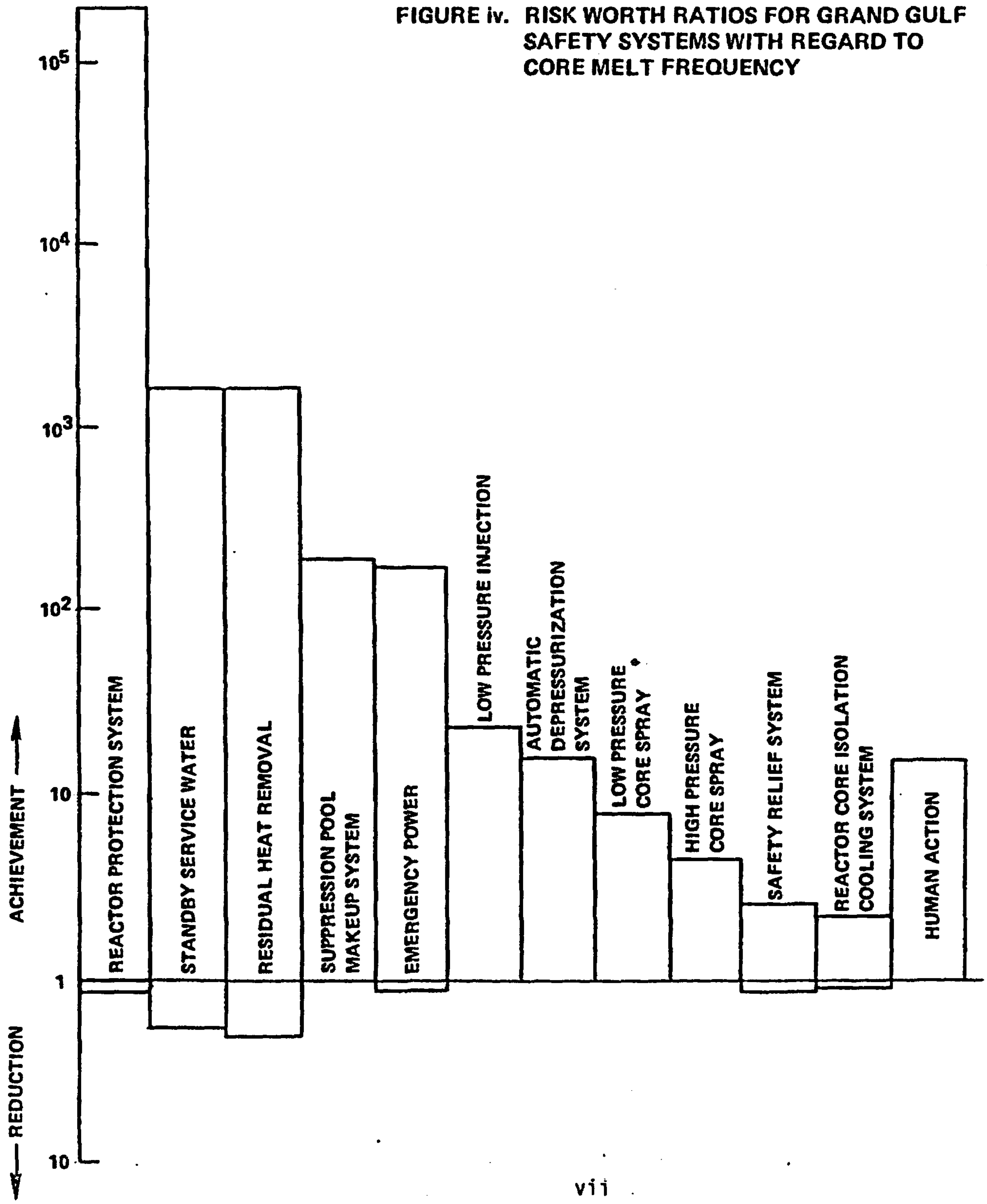


TABLE i. CONTAINMENT RISK WORTHS

Plant		Risk Reduction Worth Ratio		Risk Achievement Worth Ratio	
		Manrem	Acute Fatalities	Manrem	Acute Fatalities
Sequoyah	with V	12.5	11.8	2.12	9.09
	without V	1726.	∞	2.21	9.93
Oconee	with V	9.7	10.0	3.53	13.4
	without V	888.	∞	3.82	14.6
Calvert Cliffs		1657.	∞	2.40	8.69
Grand Gulf		2886.	∞	1.34	10.6

PROJECT OVERVIEW

This work is part of a project being conducted for the Division of Risk Analysis (DRA) of the Nuclear Regulatory Commission (NRC). The objectives of the project are to evaluate the importances of containment, the different safety functions, and other various contributers as assessed in probabilistic risk analyses and to identify generic conclusions regarding the importances. Effective display of the importances is an important part of these objectives.

To address these objectives, measures of risk importance need to be first identified and then they need to be evaluated for the different risk analyses which have been performed. This report describes the risk importance measures that were defined and were applied to the risk analyses which were performed as part of the Reactor Safety Study Methodology Applications Program (RSSMAP). The risk importance measures defined in this report measure the importance of features not only with regard to risk reduction but also with regard to reliability assurance, or risk maintenance.

The goal of this report is not to identify new mathematical formulas for risk importance but to show how importance measures can be interpreted and can be applied. When the defined risk importance measures are applied to the RSSMAP analyses, specific features and systems stand out as being more important than others. The containment worth is quantified as a function of plant and design parameters and critical variables are identified by the importance evaluations. The risk importance measures and graphic displays as applied in this report appear to be useful tools for assisting in prioritizing regulatory and research activities.

The risk importance measures identified in this report constitute only one class of measures that can be applied. Other risk importance measures which can be applied include those which quantify the importance of individual surveillance tests and maintenance activities, those which quantify where wear-out effects will have the largest risk impact, and those which prioritize contributions to uncertainty to show where data need to be collected and models need be developed. These other importance measures greatly increase the usefulness of probabilistic risk analysis and will be identified and applied in future work.

MEASURES OF RISK IMPORTANCE AND THEIR APPLICATION

1.0 INTRODUCTION

Two measures of risk importance are identified which are useful in characterizing risk properties and in aiding decision making. The two risk measures are termed the "risk achievement worth" and the "risk reduction worth". The risk achievement worth of a feature such as a safety system is the worth of the feature in achieving the present level of risk. The risk reduction worth of the feature is the worth of the feature in further reducing the risk.

To maintain the present level of risk, the features having the highest risk achievement worths will be of most interest. The risk achievement worths will thus be of special interest in reliability assurance programs and inspection and enforcement activities. To reduce the risk, the features having the highest risk reduction worths will be of most interest. The risk reduction worths will be of particular interest in plant upgrade programs and backfitting activities. If it is desired to reduce the risk, it is important not to divert attention from those features having high risk achievement worth which contribute most to the present safety of the plant. The two risk worth measures thus complement one another with regard to their characterization of what is important to risk.

The following two sections, Sections 2.0 and 3.0, explicitly define the risk achievement worth and the risk reduction worth. The relationships to other defined risk importance measures are discussed in Section 4.0. Section 5.0 discusses graphic ways to portray the risk worths and discusses ways to utilize the risk worths. Section 6.0 discusses extensions of the risk worth definitions to obtain risk impact curves useful for cost-benefit and value impact analysis.

As specific applications, Sections 7.0, 8.0, and 9.0 utilize the risk worth measures, along with sensitivity studies, to obtain insights about the risk contributors as calculated in the Reactor Safety Methodology Applications Program (RSSMAP).[1,2,3,4] RSSMAP estimated the core melt frequencies and release category frequencies from four different nuclear power plants using simplified WASH-1400 techniques. Section 7.0 outlines the RSSMAP approach, Section 8.0 evaluates the contributors to core melt frequency, and Section 9.0 focuses on the impact of containment with regard to releases and risks. In addition to providing insights about the risk contributors, the evaluations also provide insights about the effects of RSSMAP models and assumptions.

2.0 DEFINITION OF RISK ACHIEVEMENT WORTH

To measure the worth of a feature in achieving the present risk, a logical approach is to remove the feature and then determine how much the risk has increased. Thus, the risk achievement worth is formally defined to be the increase in risk if the feature were assumed not to be there or to be failed.

Depending on how the increase in risk is measured, the risk achievement worth can either be defined as a ratio or an interval. Let

R_i^+ = the increased risk level without feature i or with feature i assumed failed, (1)

and

$$R_0 = \text{the present risk level,} \quad (2)$$

where the risk can be any measure such as core melt frequency, expected dose, etc. Then on a ratio scale the risk achievement worth A_i of feature i is defined as:

$$A_i = R_i^+/R_0 \quad . \quad (3)$$

On an interval scale the risk achievement worth A_i is defined as:

$$A_i = R_i^+ - R_0 \quad . \quad (4)$$

In calculating R_i^+ with feature i removed, it is important to consider other features which are also effectively removed because of interrelationships or dependencies with feature i. Whether the ratio or interval definition is most pertinent will depend upon the particular utilization. When risk achievement worths are calculated for a given plant in order to prioritize the features then the ratio and interval definitions will generally give the same rankings. When the features of different plants are compared or when cost-benefit evaluations are performed, even for a single plant, then the interval definition is generally more appropriate. If different risk measures R_0, such as core melt frequency and expected early fatalities, are used, then different priorities can result and therefore it generally is useful to examine various risk measures to obtain a more complete picture of a feature's risk worth. Utilizations of risk achievement worths in decision making are further discussed in Section 5.0.

3.0 DEFINITION OF RISK REDUCTION WORTH

To measure the worth of a feature in reducing the present risk, a logical approach is to "optimize" the feature and then determine how much the risk has been decreased. Thus, the risk reduction worth is formally defined to be the decrease in risk if the feature were assumed to be optimized or were assumed to be made perfectly reliable.

Again, depending on how the decrease in risk is measured, the risk reduction worth can either be defined as a ratio or an interval. Let

R_i^- = the decreased risk level with the feature optimized or assumed to be perfectly reliable, (5)

and again let R_0 be the present risk level. Then on a ratio scale, the risk reduction worth D_i of feature i (the letter "D" denotes decrease) is defined as:

$$D_i = R_0/R_i^- \quad . \tag{6}$$

On an interval scale the risk reduction worth $\mathcal{D}_i$ is:

$$\mathcal{D}_i = R_0 - R_i^- \quad . \tag{7}$$

As defined in the above manner, the risk reduction worth, D_i or $\mathcal{D}_i$, is always greater than or equal to one or is always positive, respectively.

In calculating R_i^- with feature i optimized, other interrelated features which are also effectively optimized should be included. Again, whether the ratio or interval definition is used will depend upon the specific application. For a given plant and for a given risk measure, the ratio and interval will generally give the same ranking of the features. The risk reduction worths of features will depend on the risk measure being examined. As for the risk achievement worths, when the features of different plants are compared or when cost-benefit analyses are performed, then the interval definition is generally more appropriate. Utilizations of calculated risk reduction worths are further discussed in Section 5.0.

4.0 RELATIONSHIP TO OTHER IMPORTANCE MEASURES

The risk achievement worth and risk reduction worth are included in the broad class of importance measures defined by Engelbrecht-Wiggans and Strip(5). Certain of the importance measures were also utilized by K. G. Murphy(6) in his evaluation of significance of piping sections.

If the risk measure is defined to be the system unavailability or unreliability then the more generally applied Birnbaum(7) importance Δ_i of component i can be defined as:

$$\Delta_i = R_i^+ - R_i^- \quad , \tag{8}$$

where R_i^+ is the system availability with component i assumed failed and R_i^- is the system unavailability with the component assumed working. Barlow and Proschan(8) call Δ_i the reliability importance of component i.

By adding and subtracting the nominal unavailability R_0 to the right side of Equation (8) it can be seen that

$$\Delta_i = \mathcal{A}_i + \mathcal{D}_i \quad . \tag{9}$$

Thus, the Birnbaum importance is the sum of the risk achievement and risk reduction worth of component i on an interval scale. The risk achievement worth and the risk reduction worth together are thus more informative than the Birnbaum importance.

Another generally applied importance measure is the fractional contribution of i to the risk, or the Fussell-Vesely(9) measure of importance, I_i, which can be expressed as:

$$I_i = \frac{R_0 - R_i^-}{R_0} \quad , \tag{10}$$

where the numerator represents the risk due to contributor i. Equation (10) can be expressed as:

$$I_i = 1 - \frac{1}{D_i} \quad , \tag{11}$$

or

$$I_i = \frac{D_i - 1}{D_i} \quad . \tag{12}$$

Thus, the importance I_i is simply related to the risk reduction worth on a ratio scale, D_i. The risk reduction worth on a ratio scale, however, gives only partial information about the risk importance of i; the interval measure and the risk achievement worth give important additional information about the importance of i.

5.0 PORTRAYALS AND UTILIZATIONS OF THE RISK WORTHS

In addition to tabulating and ranking the risk worths, graphs and bar charts can be constructed to convey the information about the risk importance of the features. Figure 1 depicts one method of portraying both the risk achievement worth and risk reduction worth of features on the same graph. The graph can either portray worths on a ratio or interval scale and logarithmic scales can be used for the worths (y-axis) when large variations exist in their values. Note in Figure 1 that the scale on the y-axis increases in the downward direction for the risk reduction worth. This type of graph will be used in the applications presented in Sections 7.0, 8.0, and 9.0.

Once the risk worths are determined, they can be used as one guide to prioritize resources in a risk management program. The features having the highest risk achievement worths are those features indicated as being among those most important to the present safety and present risk level of the plant. Reliability assurance programs and maintenance and surveillance of the plant features can thereby be prioritized using the risk achievement worths of the features as one guide. When the achievement worths are interpreted as priorities (e.g., by normalizing by their sum) they are a relative result and are robust to various risk analysis uncertainties. The utilization of relative risk results has been recommended by a variety of individuals and groups including the Lewis Committee[10], the TMI Committee[11], and various NRC organizations.[12,13,14]

Once the risk reduction worths are determined, they too can be used to help focus and prioritize activities aimed at reducing risk. These risk reduction activities can focus modifications of plant operation or modifications of design to those features having high reduction worths. Care must be taken when considering more than one change since the present risk level, R_0, would be affected by any change. For cost-benefit or value-impact evaluations, the costs of the changes need to be balanced against the risk reduction. Since the risk reduction worth gives the maximum risk reduction possible for an improvement in the feature, the risk reduction worths can be

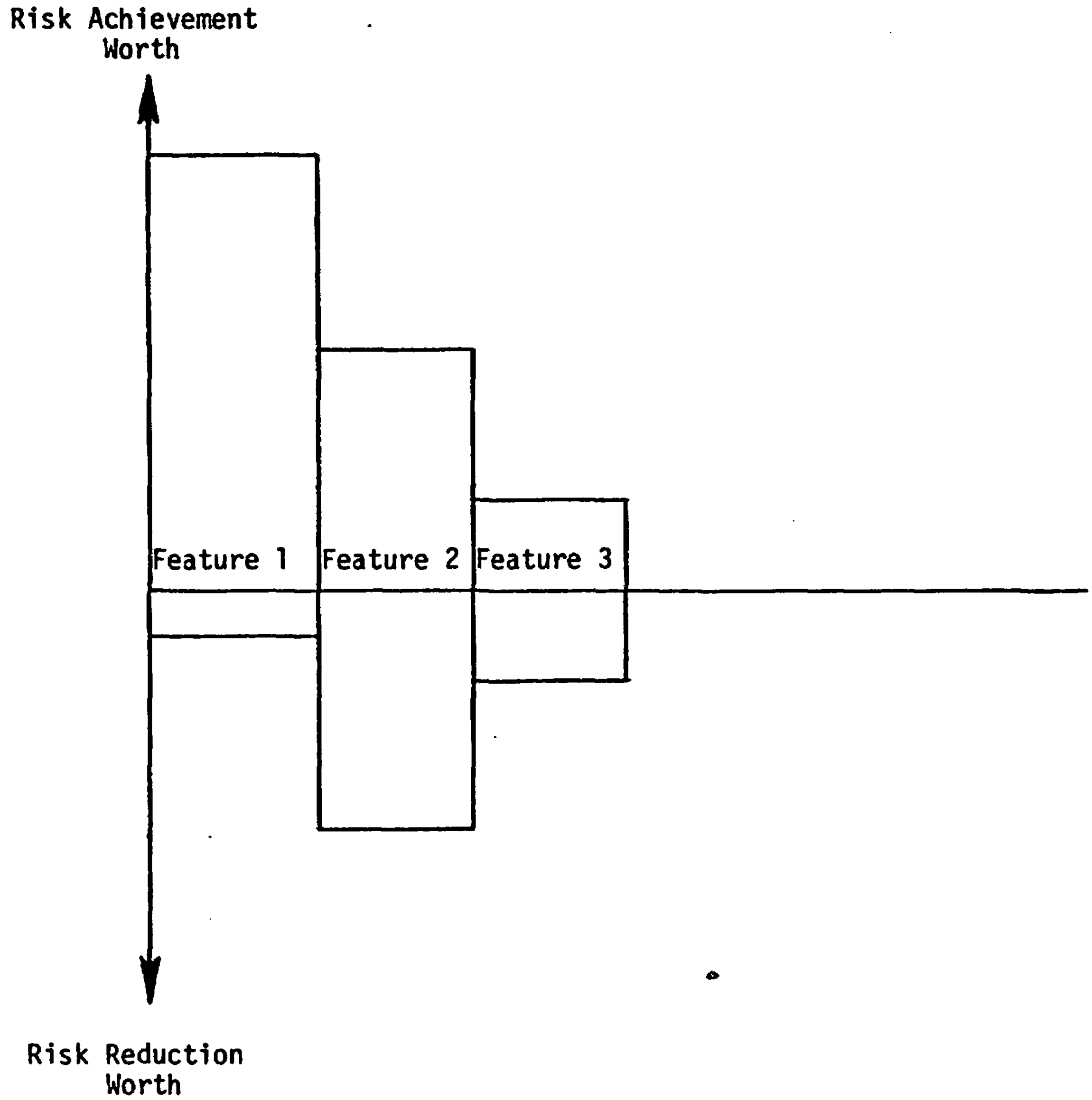


FIGURE 1. GRAPHIC PORTRAYAL OF RISK WORTHS

used to screen the modifications whose maximum risk reduction effects are inherently small compared to costs. The next section describes evaluations which are useful for cost-benefit analyses.

Calculating Risk Worths in PRA's

Calculation of the risk worths as a standard part of a PRA is straightforward. Most of the information needed to calculate the risk worths is available from a PRA. The success requirements, the system and component unavailabilities, the assumed human actions, the system dependencies, and the containment response for each sequence are quantified when performing the PRA. The sequences are also classified into release categories according to containment response and mitigative system success. The RSSMAP PRA's did not specifically evaluate consequences other than to calculate the sum of sequences in each release category. Conversion of the release category frequencies to consequences required a consequence conversion factor.

For a component, the risk reduction worth is calculated by reevaluating the boolean equations substituting zero for the unavailability of that component. The risk achievement worth for a component is calculated by substituting a value of unity for the component unavailability. For subsystems, systems, functions, or human actions similar types of manipulations and evaluations would be performed. For effective implementation, the risk worths could be calculated according to a hierarchy where the risk worths for the systems are calculated first, then the systems are successively broken down into subsystems, groups of components, and components.

Effect of Adding a System

In the case where a decision maker is evaluating the effectiveness of installing a new system to an existing plant, the risk worths can be used as a guide to the decision-maker. A system that has not yet been installed, has no risk achievement worth; however, a risk reduction worth can be estimated by evaluating the effect of the new system on the dominant sequences and estimating its availability. The decreased risk level due to the added system is then straightforwardly calculated. If a new system were added to a plant, the risk worths of the existing systems would in general also be affected.

6.0 EXTENSIONS TO RISK IMPACT CURVES

The risk achievement and risk reduction worths are somewhat gross measures of the risk importance in that the feature is either removed (assumed failed) or is assumed to be perfectly reliable in calculating the worths. As extensions of these definitions, curves of the changes in risk versus the change in the feature's failure probability or reliability can be constructed. These curves are termed "risk impact curves" since they show the impact on risk of changes in the feature's reliability. The risk impact curves can depict ratios or intervals depending upon the scale used to measure risk increases or decreases. The risk achievement worth and risk reduction worth will be two points on the curves representing limiting conditions.

Figure 2 illustrates a risk impact curve on a ratio scale; the curve depicts the risk as a function of the feature's failure probability. The risk is measured as a ratio R/R_0 relative to the present risk R_0. Similarly the feature's failure probability P is measured as a ratio P/P_0 relative to the present value P_0. The risk achievement and risk reduction worths, on a ratio scale, are associated with the two limiting points shown in the figure.

Figure 3 illustrates the risk impact on an interval scale. In this case, the risk is measured as a difference $R - R_0$ relative to the present value and the feature's failure probability is similarly measured as the difference $P - P_0$. The risk achievement and risk reduction worths, now on an interval scale, are associated with the two limiting points in the figure.

The risk impact curves for the features, particularly those on an interval scale, are useful for cost-benefit or value-impact analyses. If a set of curves is maintained as a "library", then proposed design or operation modifications need only be evaluated with regard to their impact on the feature's failure probability. The risk impact curves can then be used to relate the impact on the feature's failure probability to the impact on risk. The use of risk impact curves is made more attractive if a limited set of curves can be used to describe plant behaviors and if simple, analytical equations can be fit to the actual curves.

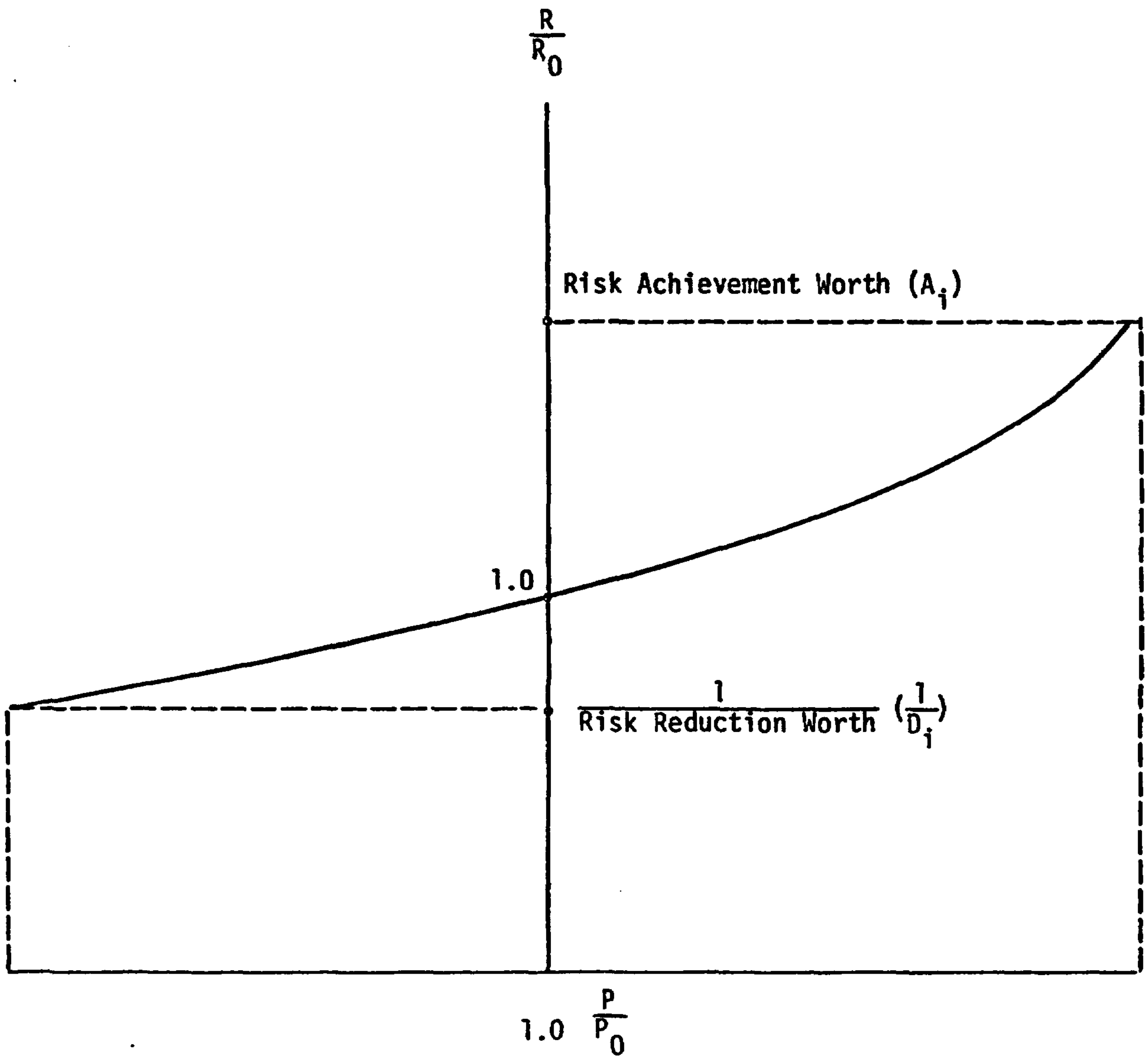


FIGURE 2. RISK IMPACT CURVE ON A RATIO SCALE

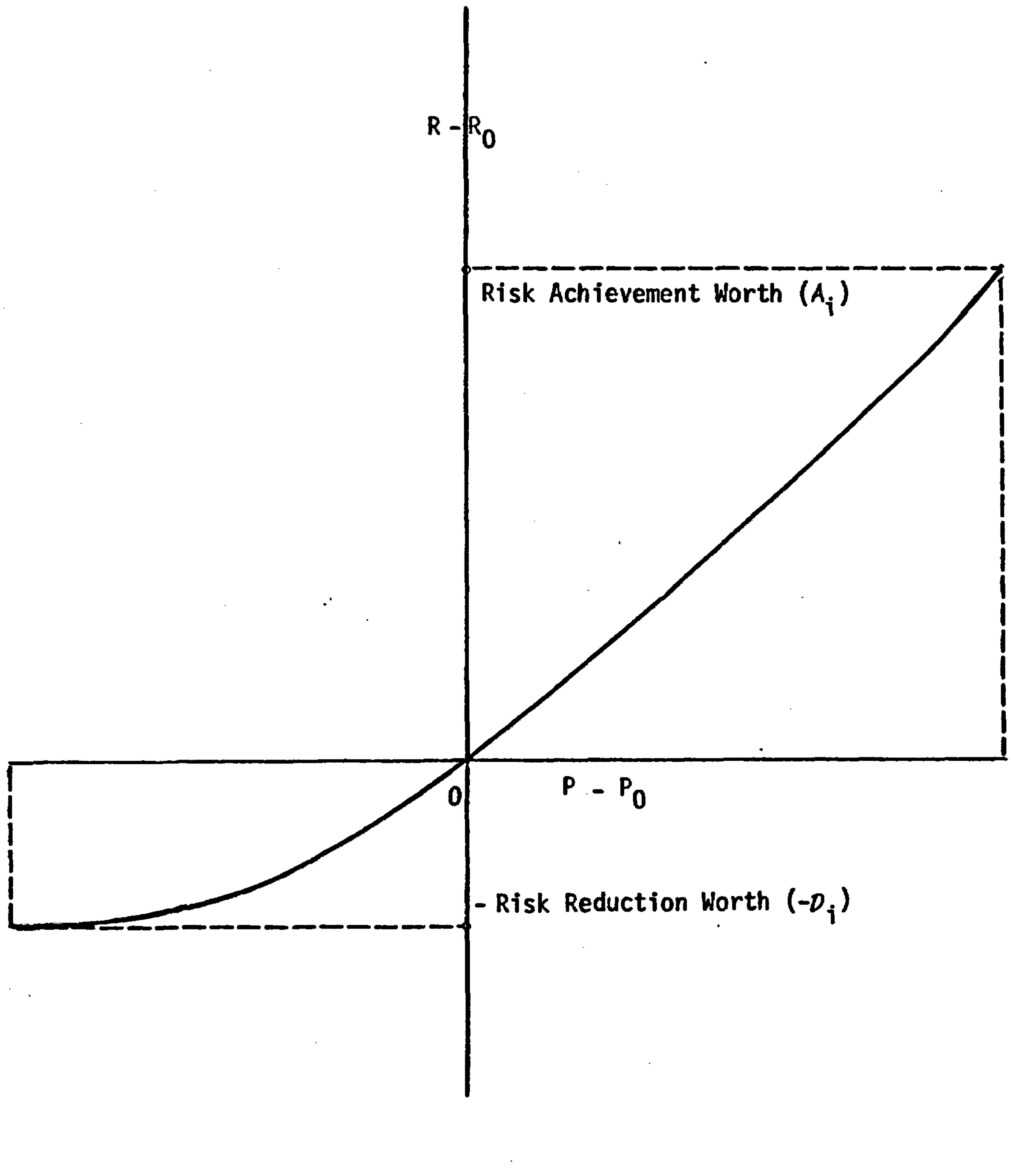


FIGURE 3. RISK IMPACT CURVE ON AN INTERVAL SCALE

7.0 RSSMAP RISK ESTIMATES

Sections 8.0 and 9.0 describe the application of the risk worth measures using the results of PRA's performed for the Reactor Safety Study Methodology Applications Program (RSSMAP) as a data base. This section provides a brief outline of the results and limitations of RSSMAP and also describes the method for estimating consequences based on RSSMAP results. These consequence estimates were used in evaluating risk worth measures for risk defined as probability times consequence. The RSSMAP program used the techniques and insights of the Reactor Safety Study[15] to perform limited risk analyses on four different plants. Plants with different reactor and containment designs were analyzed in order to broaden the class of nuclear power plants explicitly analysed in terms of risk. The important features of the four plants analyzed are summarized in Table 1.

The results of the RSSMAP analyses consisted of a set of dominant accident sequences which were assigned a failure probability for each associated containment failure mode. The sequences were then assigned to a release category. These release categories were the same ones used in the Reactor Safety Study (RSS) and were assigned based on analyses performed with the MARCH and CORRAL codes.

TABLE 1. RSSMAP PLANTS

Plant	Power Level MWe	Containment
Sequoyah #1 PWR	1148	Ice Condenser Containment
Oconee #3 PWR	886	Large Dry High Pressure Containment
Calvert Cliffs #2 PWR	850	Large Dry High Pressure Containment
Grand Gulf #1 BWR	1250	Mark III

The sequence frequencies were summed in each category to produce a frequency of release in each category. The accident sequences were determined by event tree methodology in combination with a survey and analysis technique to determine event probabilities. The system unavailabilities were quantified using the RSS hardware and human error data base.

RSSMAP was a valuable program, however in utilizing RSSMAP's results the associated limitations need to be recognized. The RSSMAP scope included equipment failures and routine human failures but did not include external events or fires. Also, the RSSMAP analyses were conducted using design information provided in the Final Safety Analysis Reports (FSAR) and did not necessarily reflect the as-built systems. The success/failure criteria used in the RSSMAP analyses were based on the FSAR analyses and the plant technical specifications which may indicate more conservative criteria and guidelines than are actually required for system success. It should be mentioned that in several cases changes to the plant designs and procedures made subsequent to the RSSMAP analyses are not included in the RSSMAP results and therefore are not included in these analyses. The RSSMAP analyses further used only point estimates and did not explicitly estimate uncertainties.

RSSMAP's limitations imply that conclusions drawn from the results need to be checked before any action is taken. Recognizing the limitations, RSSMAP's results are a useful data base for drawing tentative conclusions on the importance of features to core melt frequency and to risk. RSSMAP's results will also serve to illustrate the information which is obtainable from calculating the risk achievement worth and risk reduction worth for different features.

The risk reduction worth and risk achievement worth defined in this report can be calculated using various risk measures. The three risk measures chosen were core melt frequency, expected dose within 50 miles, and expected acute fatalities. These three measures provide a characterization of the health risks. Other measures such as environmental degradation and economic impact could be treated similarly if desired and may be of interest for cost-benefit studies.

Using the approach in Andrews et al[16], a consequence factor in terms of manrem and acute fatalities was associated with each release category defined in RSSMAP. The consequence factors used for each RSSMAP plant were scaled linearly to the power level of the plant used in Reference 16 (1120 MWe). The consequence factors for the base plant are shown in Table 2. The expected dose and expected acute fatalities are determined by summing the product of the release category frequency and the appropriate consequence factor.

The reader should recognize that the use of RSS release categories is likely to lead to an over-estimate of the consequences of accident sequences. Since the Reactor Safety Study, research has been directed at obtaining a better understanding of retention mechanisms which would reduce the quantity of fission products released from the plant in an accident. The NRC is currently undertaking a study to revise the RSS release categories but the results of that study were not yet available to the work that is the subject of this report. Even though the consequences may be high, the relative information obtained from the risk achievement and risk reduction worths is still useful.

TABLE 2. CONSEQUENCE FACTORS FOR A REFERENCE 1120 MWe PLANT[1]

Category	Man Rem	Acute Fatalities
PWR		
1	1.6×10^6	340.
2	1.4×10^6	69.
3	1.6×10^6	87.
4	7.9×10^5	14.
5	3.0×10^5	0.14
6	4.3×10^4	0
7	$6.8 \quad 10^2$	0
BWR		
1	1.6×10^6	91.
2	2.1×10^6	53.
3	1.5×10^6	8.
4	1.8×10^5	0

(1) The consequence factors were estimated using the CRAC 2 program assuming the meteorological data from a typical midwest site (Braidwood). A uniform population density of 100 persons per square mile was assumed with an exclusion area of 1/2 mile. No evacuation was considered. The units of the consequence factors are expected dose within 50 miles per event and expected number of early fatalities per event.

8.0 WORTHS OF FEATURES WITH REGARD TO CORE MELT FREQUENCY

The risk reduction and risk achievement worths were calculated for the major safety functions and the safety systems in Sequoyah, Oconee, Calvert Cliffs, and Grand Gulf. In addition, the worths of the human actions and human errors identified in RSSMAP for the four plants are also calculated. The risk worths are given here for core melt frequency. Use of the other risk measures (expected manrem and expected early fatalities) gives similar results with regard to the importance of features in a given plant. Examples of the risk worths for these other risk measures are given in Appendix A.

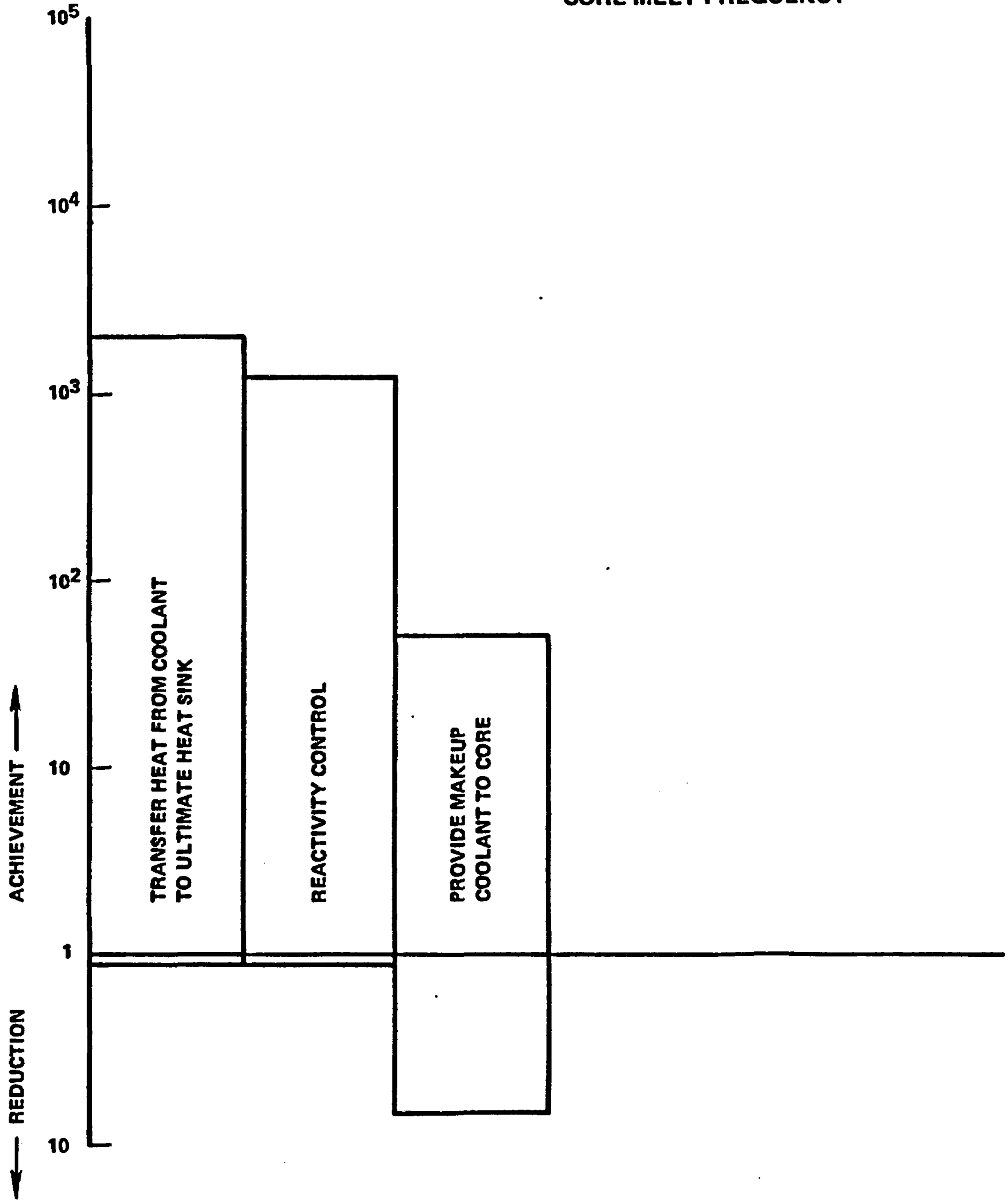
The chapter is arranged as follows: Sections 8.1, 8.2, 8.3, and 8.4 present the risk worths for Sequoyah, Oconee, Calvert Cliffs, and Grand Gulf, respectively. In each section tables and figures of the worths are given and observations are made. Section 8.5 then compares the four plants with regard to differences in the worths. Tables and figures are again given and observations are made about the differences. Section 8.6 presents example risk benefit curves for a few important systems.

8.1 Sequoyah

The risk worths for the different safety functions are shown in Table 3. The risk worth ratios are also displayed graphically in Figure 4. The safety functions are broken down to a system level and the results for the selected safety systems are presented in Table 4. Some of the other systems such as the low pressure recirculation system and service water were not analyzable due to the limitations of Sequoyah study. The risk worth ratios for the RSSMAP identified systems are shown in Figure 5.

The Sequoyah study identified one human error that was a contributor to the risk estimates. This was a common mode error which disabled the emergency core cooling recirculation system (ECCR) and the containment sprays. The risk worths for this error are shown in Table 5. The risk worth ratios are shown in Figure 6.

FIGURE 4. RISK WORTH RATIOS FOR SEQUOYAH SAFETY FUNCTIONS WITH REGARD TO CORE MELT FREQUENCY



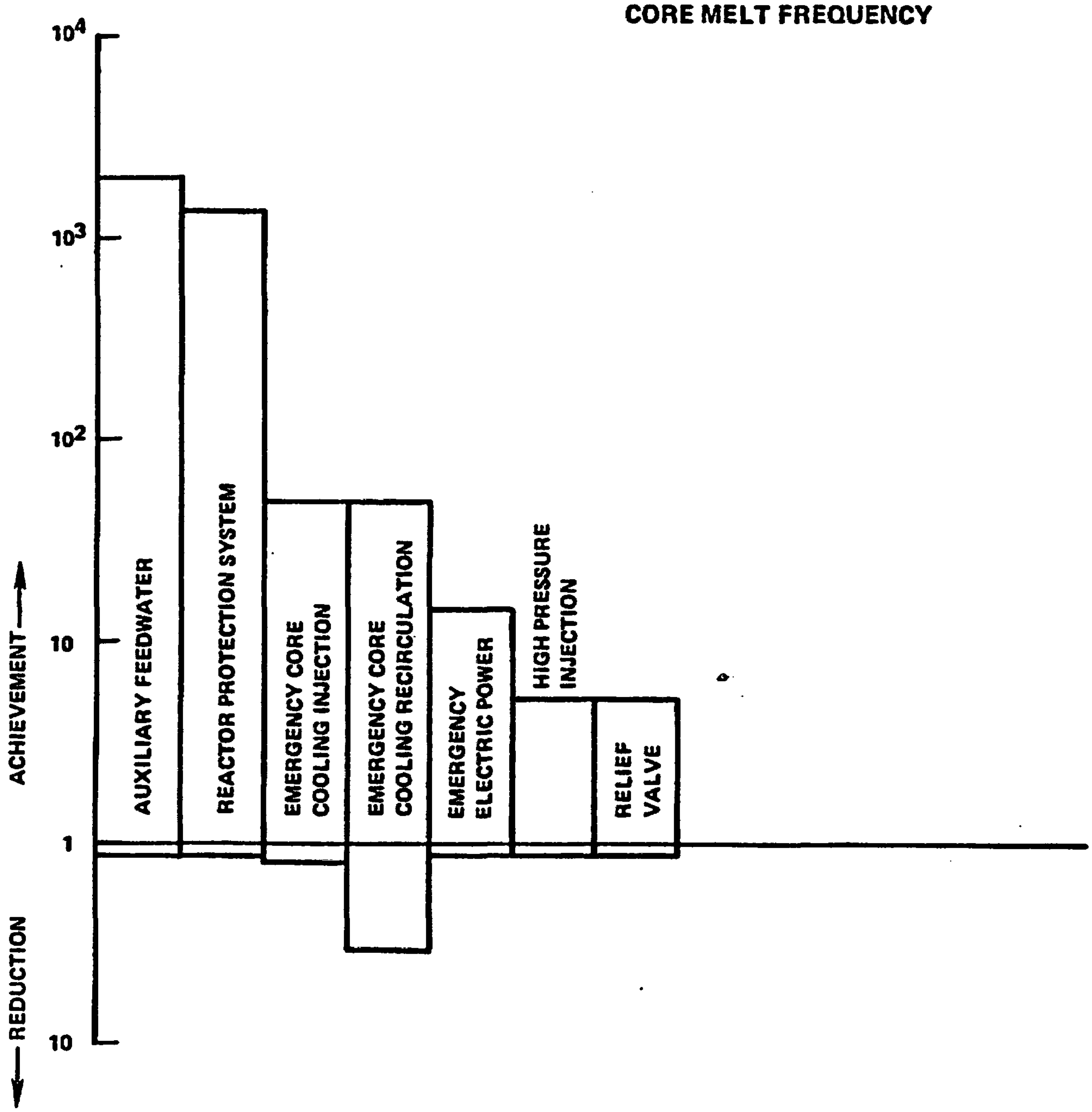


FIGURE 5. RISK WORTH RATIOS FOR SEQUOYAH SAFETY SYSTEMS WITH REGARD TO CORE MELT FREQUENCY

FIGURE 6. RISK WORTH RATIOS OF HUMAN ACTIONS AT SEQUOYAH WITH REGARD TO CORE MELT FREQUENCY

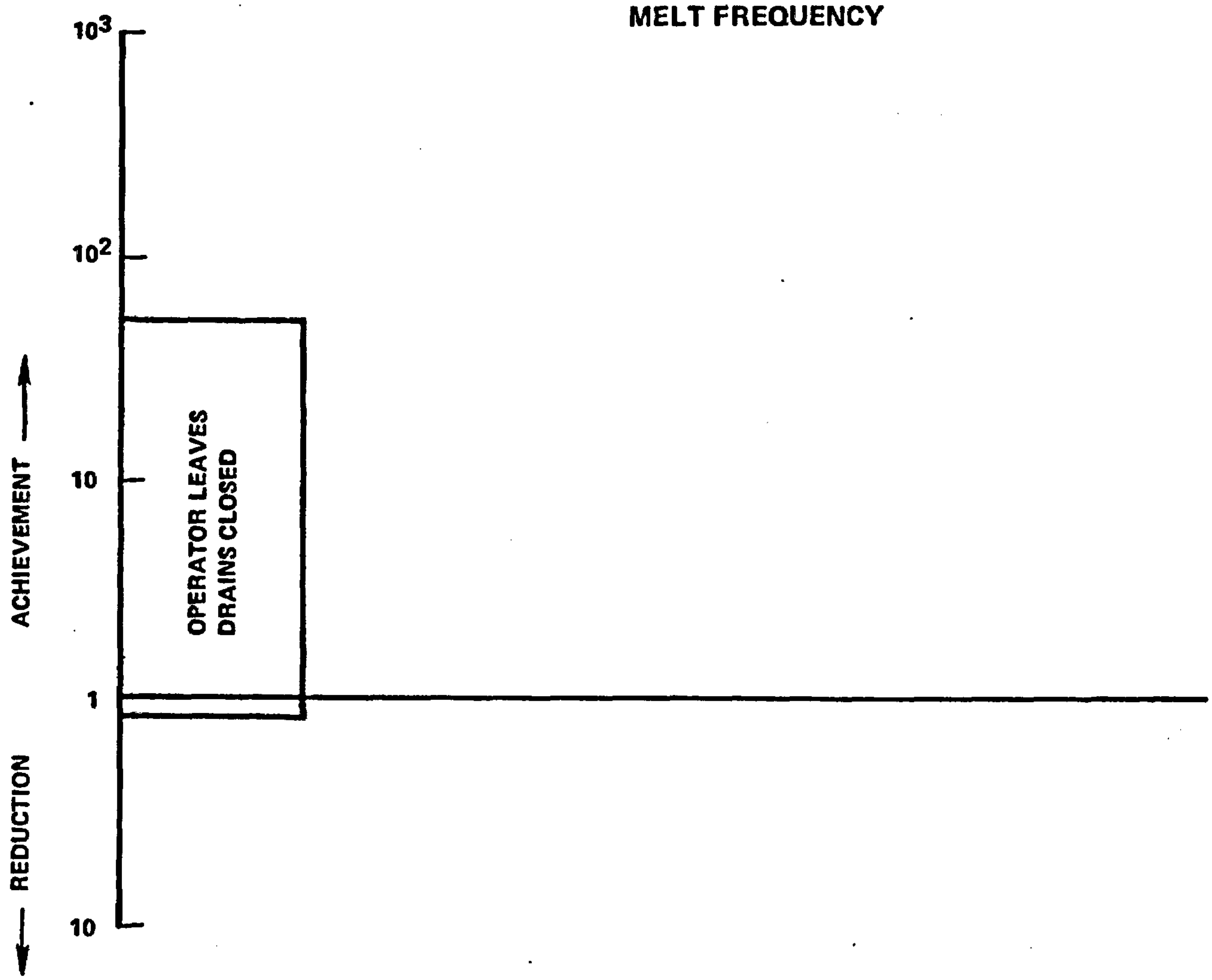


TABLE 3. RISK WORTHS FOR SEQUOYAH SAFETY FUNCTIONS WITH REGARD TO CORE MELT FREQUENCY

Function	Risk Reduction Interval	Risk Reduction Ratio	Risk Achievement Interval	Risk Achievement Ratio
Reactivity Control	2.5×10^{-6}	1.1	7.1×10^{-2}	1200
Provide Emergency Coolant to Core	5.3×10^{-5}	7.0	2.8×10^{-3}	50
Transfer Heat From Coolant to Ultimate Heat Sink (not including main power conversion system)	3.0×10^{-6}	1.1	7.0×10^{-2}	2000

TABLE 4. RISK WORTHS FOR SEQUOYAH SYSTEMS

System	Risk Reduction Interval	Risk Reduction Ratio	Risk Achievement Interval	Risk Achievement Ratio
Auxiliary Feedwater	3.0×10^{-6}	1.1	1.1×10^{-1}	2000
Pressurizer Relief Valve (stuck open)	2.5×10^{-6}	1.1	2.5×10^{-4}	5.3
High Pressure Injection	2.8×10^{-7}	1.0	2.5×10^{-4}	5.3
Emergency Core Cooling Injection	1.0×10^{-5}	1.2	2.8×10^{-3}	50
Emergency Core Cooling Recirculation	3.8×10^{-5}	3.1	2.8×10^{-3}	50
Emergency Electric Power	7.6×10^{-7}	1.0	7.0×10^{-4}	14
Reactor Protection System	2.5×10^{-6}	1.1	7.0×10^{-2}	1200

TABLE 5. RISK WORTHS OF HUMAN ERRORS AT SEQUOYAH WITH REGARD TO CORE MELT FREQUENCY

Human Action	Risk Reduction Interval	Risk Reduction Ratio	Risk Achievement Interval	Risk Achievement Ratio
Operator Leaves Drains Between Upper and Lower Containment Volume in Closed Position	8.0×10^{-6}	1.2	2.7×10^{-3}	50

From the results of the Sequoyah analysis, the following observations can be made. At the functional level, the risk reduction worths for the reactivity control and heat transfer to ultimate sink functions are quite low indicating only a small (~10 percent) potential for risk reduction could be achieved by further improving these systems. A risk reduction of approximately an order of magnitude, however, is possible by optimizing the emergency coolant supply to the core.

The risk achievement ratio worths for the heat transfer function and for reactivity control are about 3 orders of magnitude and are about 20 times more important than the emergency coolant function. The ratio worth for the emergency coolant function is however still significant, being about a factor of 50. These risk worths indicate the reduction in core melt frequency which occurs due to the presence of the existing safety functions.

With regard to risk reduction ratio worths at the system level the largest value is a factor of 3 for the emergency core coolant recirculation system (ECCR). All other system ratio worths are less than a factor of 2 and in fact are very close to 1. All these values indicate marginal or insignificant improvement in core melt frequency with system improvement.

The risk achievement worths graphed in Figure 5 point out the importance of the reactor protection system and the auxiliary feedwater system in achieving the present risk level. The core melt frequency would be more than 3 orders of magnitude higher if these systems were not functioning. The ECC systems and the emergency power system (EPS) also have risk achievement worths between 1 and 2 orders of magnitude for Sequoyah. The other two systems that were analyzed had risk achievement worths of a factor of 5.

The systems which shut down the nuclear reactor (RPS) and remove the decay heat (AFWS) are very important in preventing core melt, and this is reflected by their high risk achievement values. The emergency core cooling injection and recirculation systems are also shown to be important. This reflects the relative importance of LOCA's in the predicted core melt frequency at Sequoyah. The systems which are called upon during transients (HPI and PORV) have relatively low risk achievement worths reflecting the predicted low importance of transients leading to core melt at Sequoyah. These results in addition to prioritizing system worths, thus also reflect the models and analyses utilized in RSSMAP.

For the human error analyzed, a small core melt frequency reduction (~20 percent) was possible whereas a significant risk achievement value of a factor of 50 was calculated. The risk achievement ratio indicates that as presently carried out, the human activity results in a factor of 50 reduction in core melt frequency. This worth compares with the worths of 2000 and 1200 for the auxiliary feedwater system and the reactor protection system. The high achievement worth and low reduction worth for the human error indicates that the human activity is presently being performed with a near optimal reliability as modeled by RSSMAP. The generally high achievement worths and low reduction worths indicate that attention should be focused on maintaining and assuring the present reliabilities as opposed to formulating retrofits to upgrade them. (This does not say that new systems may not have significant risk reduction effects, however.)

8.2 Oconee

The risk worths at the functional level for Oconee are shown in Table 6. The risk worth ratios are also displayed graphically in Figure 7. The results for specific systems are shown in Table 7 and Figure 8. The Oconee study identified a number of human actions which were important to risk. These have been evaluated and tabulated in Table 8. The risk worth ratios for these human actions are shown in Figure 9.

FIGURE 7. RISK WORTH RATIOS FOR OCONEE SAFETY FUNCTIONS WITH REGARD TO CORE MELT FREQUENCY

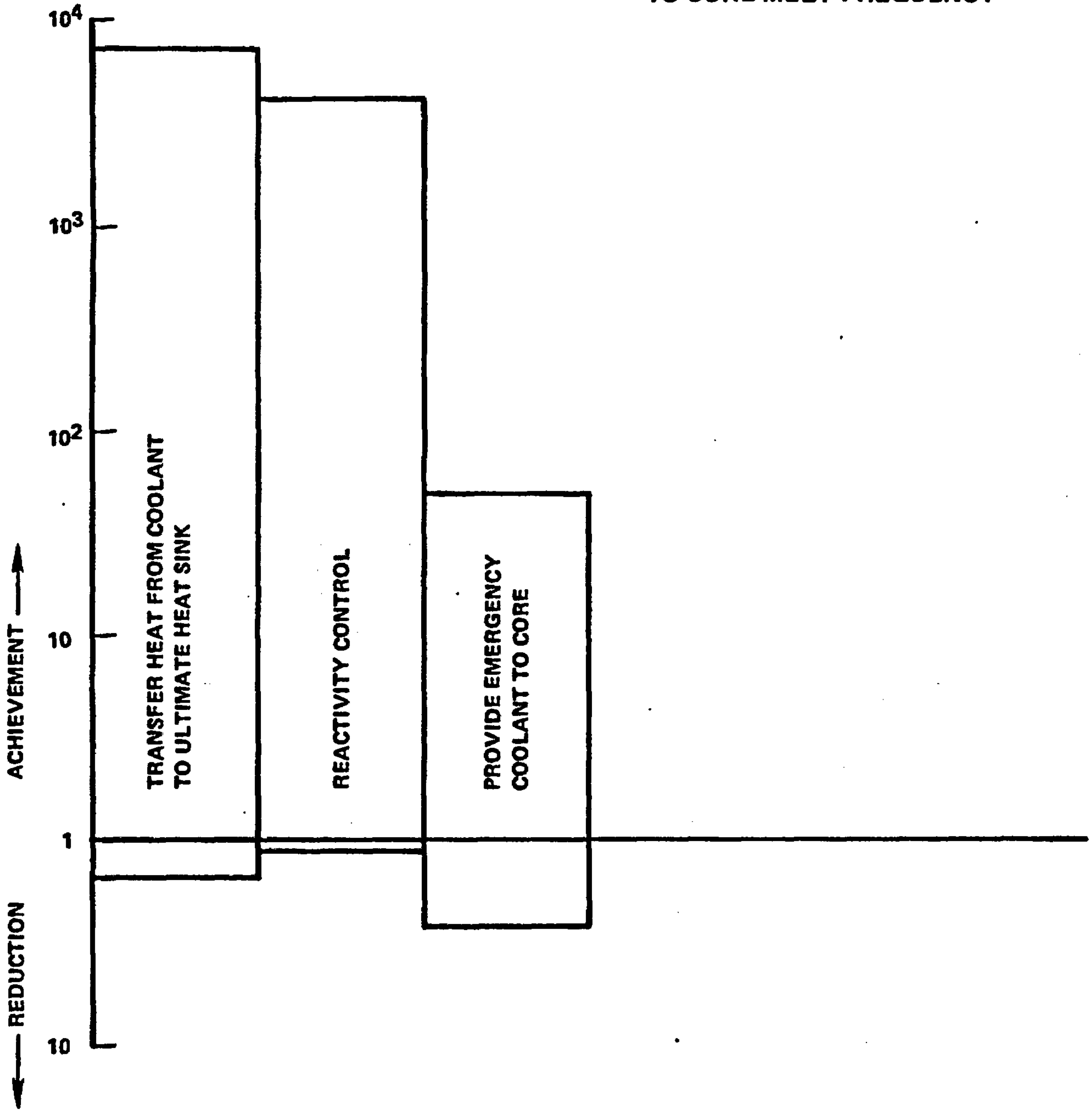


FIGURE 8. RISK WORTH RATIOS FOR OCONEE SAFETY SYSTEMS WITH REGARD TO CORE MELT FREQUENCY

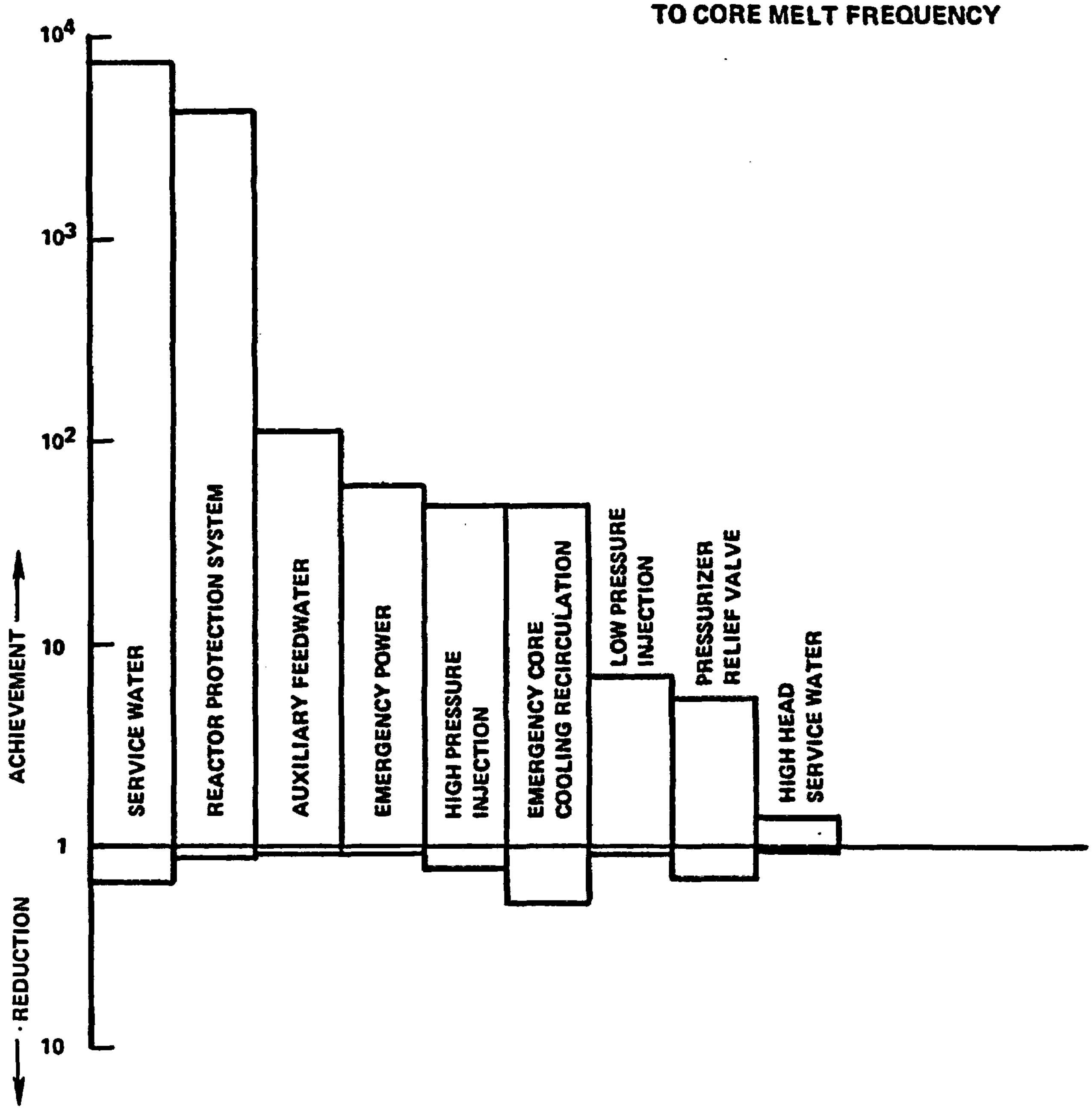


FIGURE 9. RISK WORTHS OF IMPORTANT HUMAN ACTIONS AT OCONEE WITH REGARD TO CORE MELT FREQUENCY

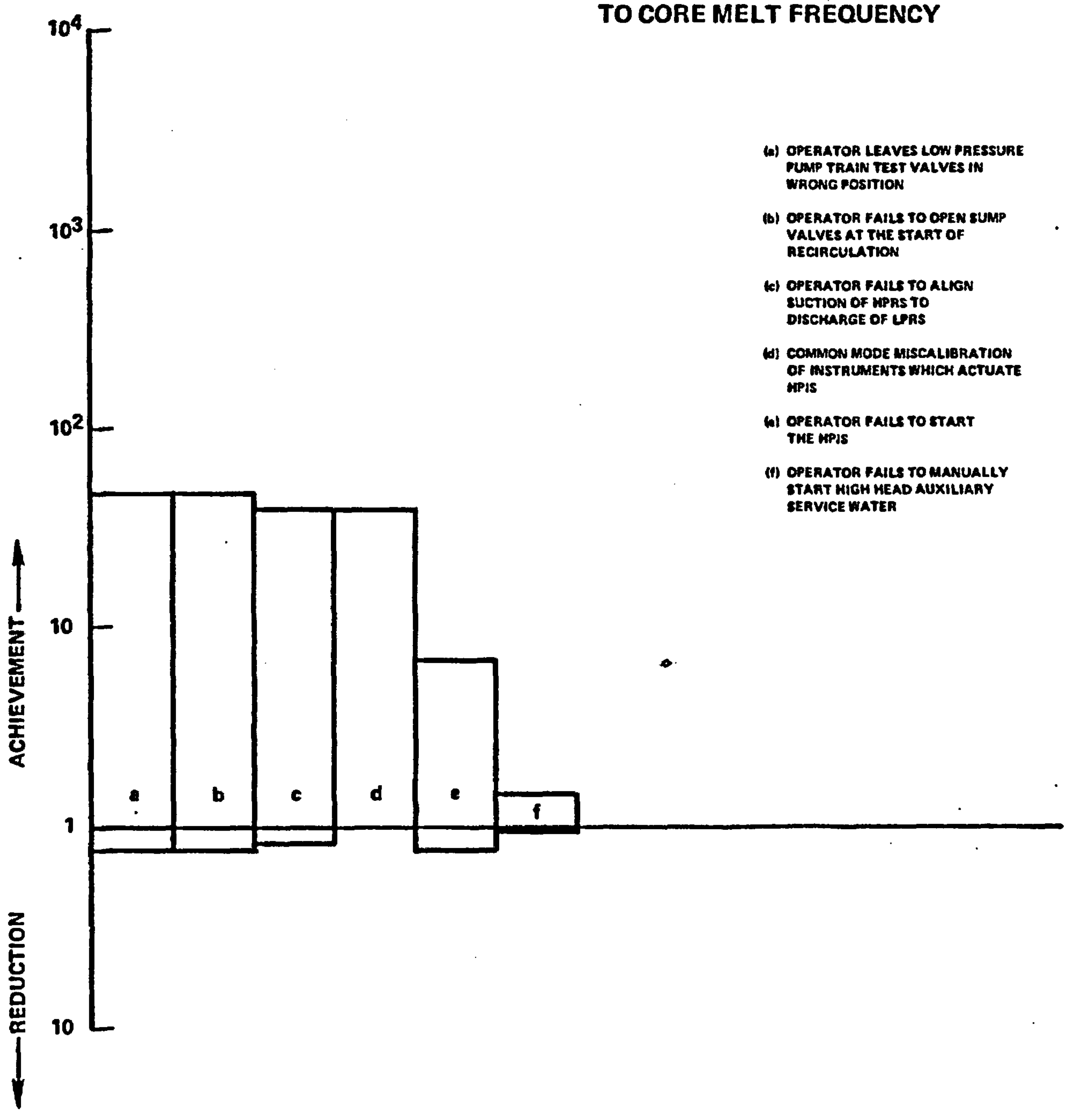


TABLE 6. RISK WORTHS FOR OCONEE SAFETY FUNCTIONS WITH REGARD TO CORE MELT FREQUENCY

Function	Risk Reduction		Risk Achievement	
	Interval	Ratio	Interval	Ratio
Reactivity Control	7.8×10^{-6}	1.1	.32	4100
Provide Emergency Coolant to Core	4.3×10^{-5}	2.5	3.4×10^{-3}	48
Transfer Heat From Coolant to Ultimate Heat Sink (not including normal power conversion system)	2.0×10^{-5}	1.4	0.54	7500

TABLE 7. RISK WORTHS FOR OCONEE SYSTEMS WITH REGARD TO CORE MELT FREQUENCY

System	Risk Reduction		Risk Achievement	
	Interval	Ratio	Interval	Ratio
Auxiliary Feedwater	3.0×10^{-6}	1.0	7.5×10^{-3}	110
High Head Service Water	2.2×10^{-6}	1.0	2.0×10^{-5}	1.3
Pressurizer Relief Valve (stuck open)	1.8×10^{-5}	1.3	3.3×10^{-4}	5.6
High Pressure Injection	1.4×10^{-5}	1.2	3.4×10^{-3}	48
Low Pressure Injection	8.8×10^{-6}	1.1	5.0×10^{-4}	7.0
Emergency Core Cooling Recirculation	3.3×10^{-5}	1.9	3.4×10^{-3}	48
Low Pressure Service Water	1.5×10^{-5}	1.3	0.54	7500
Electric Power (onsite)	2.2×10^{-6}	1.0	4.4×10^{-3}	62
Reactor Protection System	7.8×10^{-6}	1.1	0.30	4100

TABLE 8. RISK WORTHS OF IMPORTANT HUMAN ACTIONS AT OCONEE WITH REGARD TO CORE MELT FREQUENCY

Human Action	Risk Reduction		Risk Achievement	
	Interval	Ratio	Interval	Ratio
Operator Leaves Low Pressure Pump Train Test Valves in Wrong Position	9.9×10^{-6}	1.2	3.3×10^{-3}	47
Operator Fails to Open Sump Valves at the Start of Recirculation	9.6×10^{-6}	1.2	3.2×10^{-3}	45
Operator Fails to Align Suction of HPRS to Discharge of LPRS	8.4×10^{-6}	1.1	2.8×10^{-3}	40
Common Mode Miscalibration of Instruments Which Actuate HPIS	9.0×10^{-8}	1.0	2.7×10^{-3}	40
Operator Fails to Start the HPIS	1.3×10^{-5}	1.2	4.3×10^{-4}	6.9
Operator Fails to Manually Start High Head Auxiliary Service Water	2.2×10^{-6}	1.0	1.9×10^{-5}	1.3

The following observations can be made regarding the Oconee results. At the functional level the risk reduction potential is small for reactivity control and heat transfer to the ultimate heat sink functions. The risk reduction potential for the emergency coolant supply function is somewhat larger but is still less than a factor of three.

The risk achievement worths are all considerably higher than the risk reduction worths. The ratio worths for the reactivity control and the heat removal functions are between 3 and 4 orders of magnitude. The worth for the emergency coolant supply function is about a factor of 50. These risk achievement worths indicate the present degree of protection provided by the different functions.

At the system level all the risk reduction worths are quite small, the largest being a factor of 2 for the emergency core coolant recirculation system. The risk achievement worths for Oconee safety system range over almost 4 orders of magnitude. The low pressure service water system and the reactor protection system stand out as being particularly important with risk achievement ratios of 3 to 4 orders of magnitude. The auxiliary feedwater, the emergency power supply, the high pressure injection, and the emergency core cooling recirculation systems also have high risk achievement factors of about 50 to 100 which are significant. The low pressure injection system and the pressurizer relief valve have risk achievement factors of about 5 to 10. The high head service water has a factor of only 1.3. The low pressure service water system has a very high worth (7500) because the auxiliary feedwater, the diesels, and all of the emergency coolant pumps depend on the operation of the service water for component cooling. Failure of the low pressure service water system lead to failure in the other systems in a short time.

The high head service water, on the other hand, shows a low risk achievement worth. This system is designed to be used as an alternative to the auxiliary feedwater system in the case of loss of onsite and offsite power. Since the onsite power at Oconee is predicted to be very reliable, this system is not expected to be needed frequently, consequently a low risk achievement worth is calculated.

The risk worth of human actions shown in Table 8 and Figure 9 indicate low risk reduction worths. Further improvement in the assumed operator performance of any particular action would not significantly reduce risk estimates. The potential increases in risk attributed to degradation of present predicted human reliability however can be quite significant.

If desired, the system can be divided into subsystems and/or further divided into components. The risk worths can then be calculated for each subsystem or component. This gives useful information regarding the relative importance of each subsystem or component. Inspection, testing, and maintenance efforts can be focused on the most important components based on the results.

The results for one of the most important systems (low pressure service water) at the subsystem level have been calculated as an example. This system at Oconee consists of two redundant trains. One train is normally operating while the other is in standby.

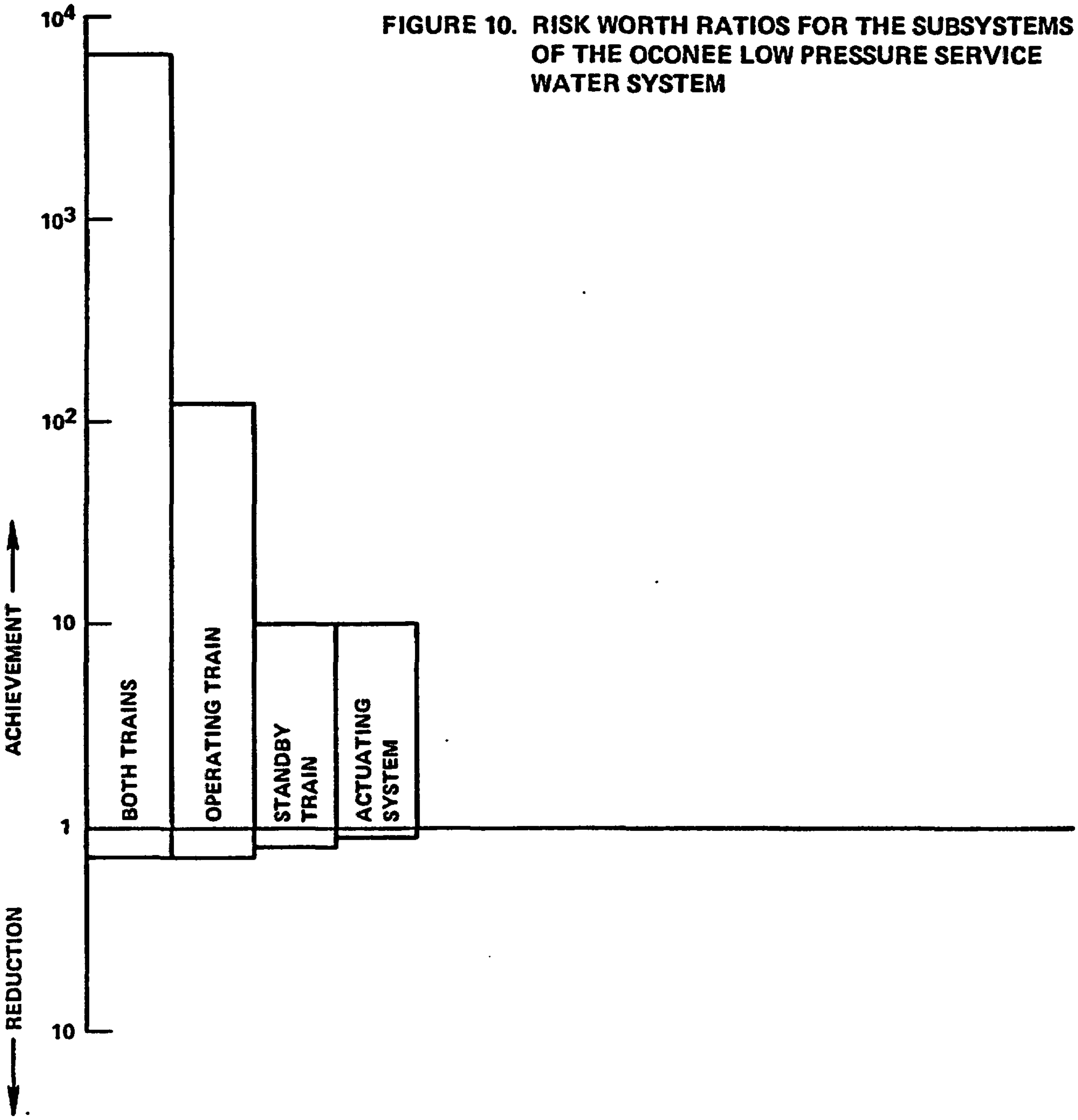
System failure requires the operating train to fail along with failure to start and run the standby train. The system can be divided into three subsystems: the operating train, the standby train, and the actuating system for the standby train. The risk worths at the subsystem level are presented in Table 9 for each subsystem. The risk worth ratios are presented in Figure 10. The potential risk reductions obtainable from making a subsystem more reliable are small, about a factor of 1.2 or less. The risk achievement factors are about 2 orders of magnitude for the operating train and 1 order of magnitude for the standby train. The factor of 10 increase in risk can be interpreted as the increase in risk level when one of the service water trains is down, e.g. out for maintenance.

The generally high risk achievement ratios and low risk reduction ratios again indicate that attention should be focused on reliability assurance and risk maintenance activities with these activities in turn focused on the areas of highest achievement worths.

TABLE 9. RISK WORTHS FOR THE SUBSYSTEMS OF THE OCONEE LOW PRESSURE SERVICE WATER SYSTEM

Subsystem	Risk Reduction		Risk Achievement	
	Interval	Ratio	Interval	Ratio
Normally Operating Service Water Train	1.5×10^{-5}	1.3	1.0×10^{-2}	120
Standby Service Water Train	1.1×10^{-5}	1.2	7.6×10^{-4}	10
Actuating System for Standby Train	3.8×10^{-6}	1.1	7.6×10^{-4}	10
Both Trains of Low Pressure Service Water	1.5×10^{-5}	1.3	0.54	7500

FIGURE 10. RISK WORTH RATIOS FOR THE SUBSYSTEMS OF THE OCONEE LOW PRESSURE SERVICE WATER SYSTEM



8.3 Calvert Cliffs

The results of the Calvert Cliffs analysis predicted a significantly higher core melt frequency than at the other three RSSMAP plants. This was primarily due to sequences involving failure of the emergency feedwater systems and the assumed inability to establish a "feed and bleed" cooling mode in time to prevent core melt.

The Calvert Cliffs analysis was based on an auxiliary feedwater system that was scheduled to be upgraded. This upgrade was predicted to have significant effects on the sequences which dominate risk at Calvert Cliffs. A rough preliminary estimate of the upgrade reduces the predicted core melt frequency by a factor of 5 from 2×10^{-3} to 4×10^{-4} per reactor year. The calculations of the risk achievement worths and risk reduction worths did not include the effects of the scheduled upgrade.

The risk worths at the functional level for Calvert Cliffs are shown in Table 10. The risk worth ratios are displayed graphically in Figure 11. The results at the system level are shown in Table 11 and Figure 12. The Calvert Cliffs analysis identified a number of human actions which were important to risk. These have been evaluated and tabulated in Table 12. The risk worth ratios for these human actions are shown in Figure 13.

TABLE 10. RISK WORTHS FOR CALVERT CLIFFS SAFETY FUNCTIONS WITH REGARD TO CORE MELT FREQUENCY

Function	Risk Reduction Interval	Risk Reduction Ratio	Risk Achievement Interval	Risk Achievement Ratio
Reactivity Control	6.0×10^{-5}	1.0	3.0	1500
Provide Emergency Coolant to Core	7.4×10^{-5}	1.0	3.3×10^{-3}	2.6
Transfer Heat From Coolant to Ultimate Heat Sink (not including main power conversion system)	1.9×10^{-3}	28	0.54	270

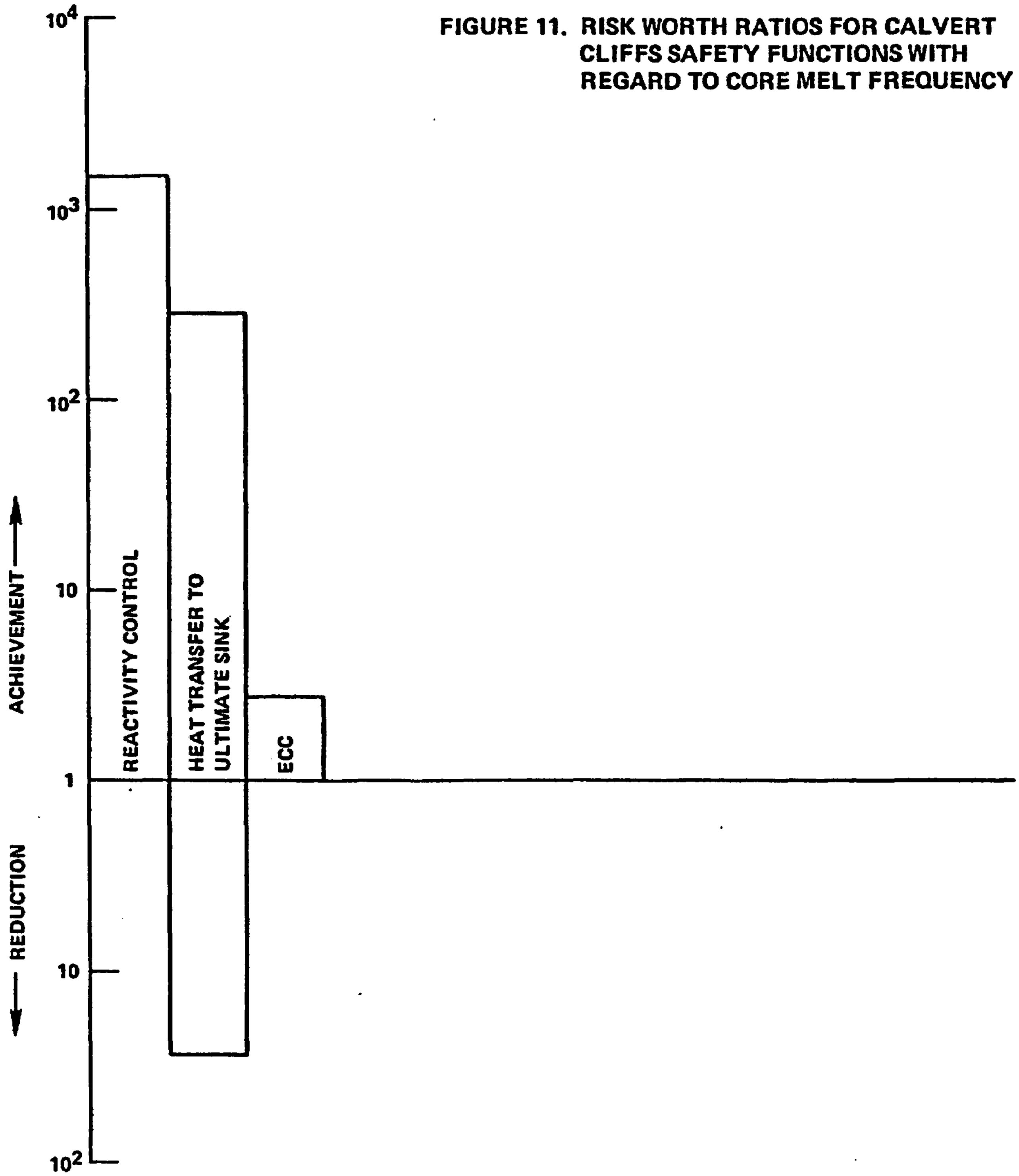


FIGURE 11. RISK WORTH RATIOS FOR CALVERT CLIFFS SAFETY FUNCTIONS WITH REGARD TO CORE MELT FREQUENCY

FIGURE 12. RISK WORTH RATIOS FOR CALVERT CLIFFS SAFETY SYSTEMS WITH REGARD TO CORE MELT FREQUENCY

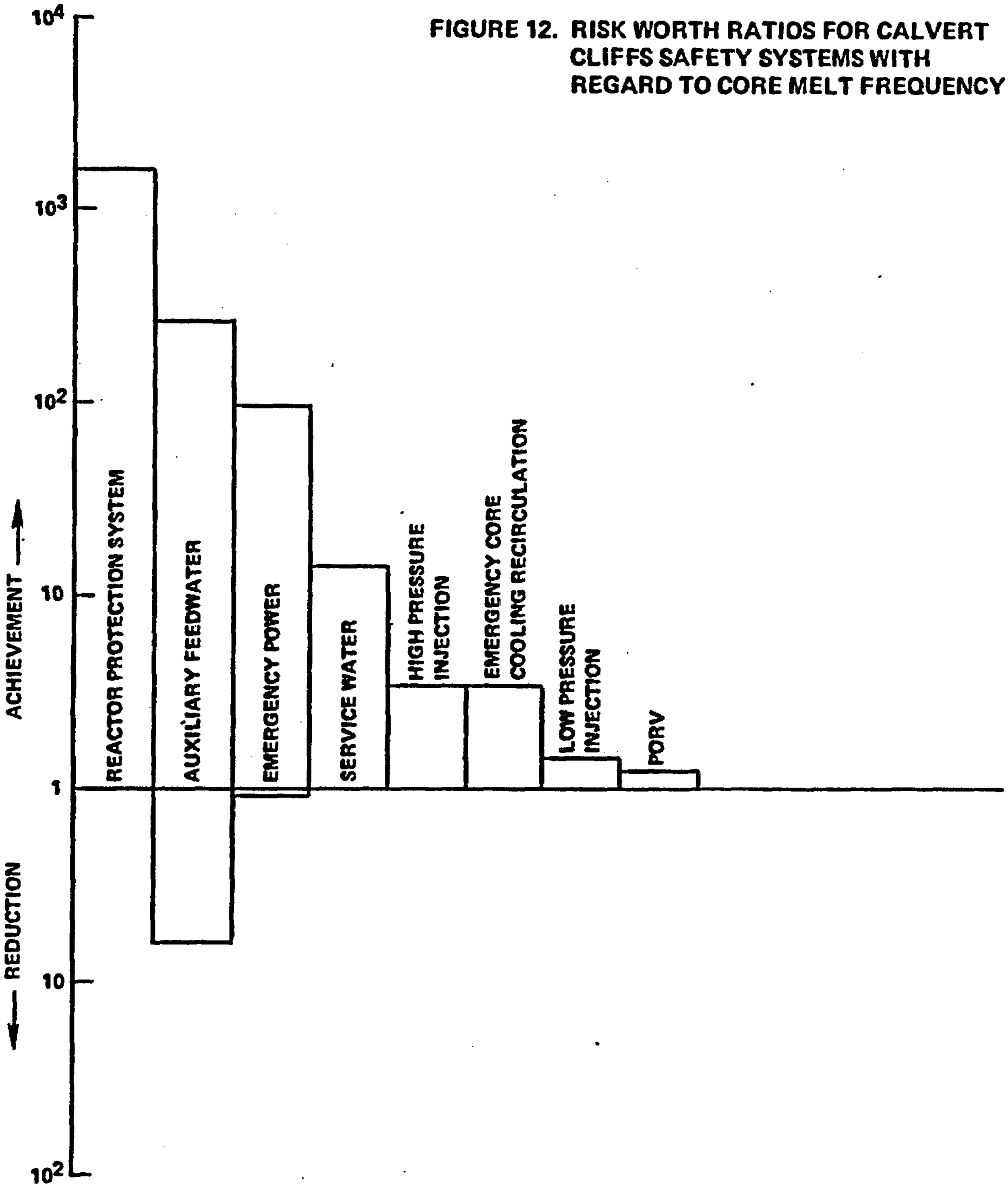


FIGURE 13. RISK WORTHS FOR HUMAN ACTIONS AT CALVERT CLIFFS WITH REGARD TO CORE MELT FREQUENCY

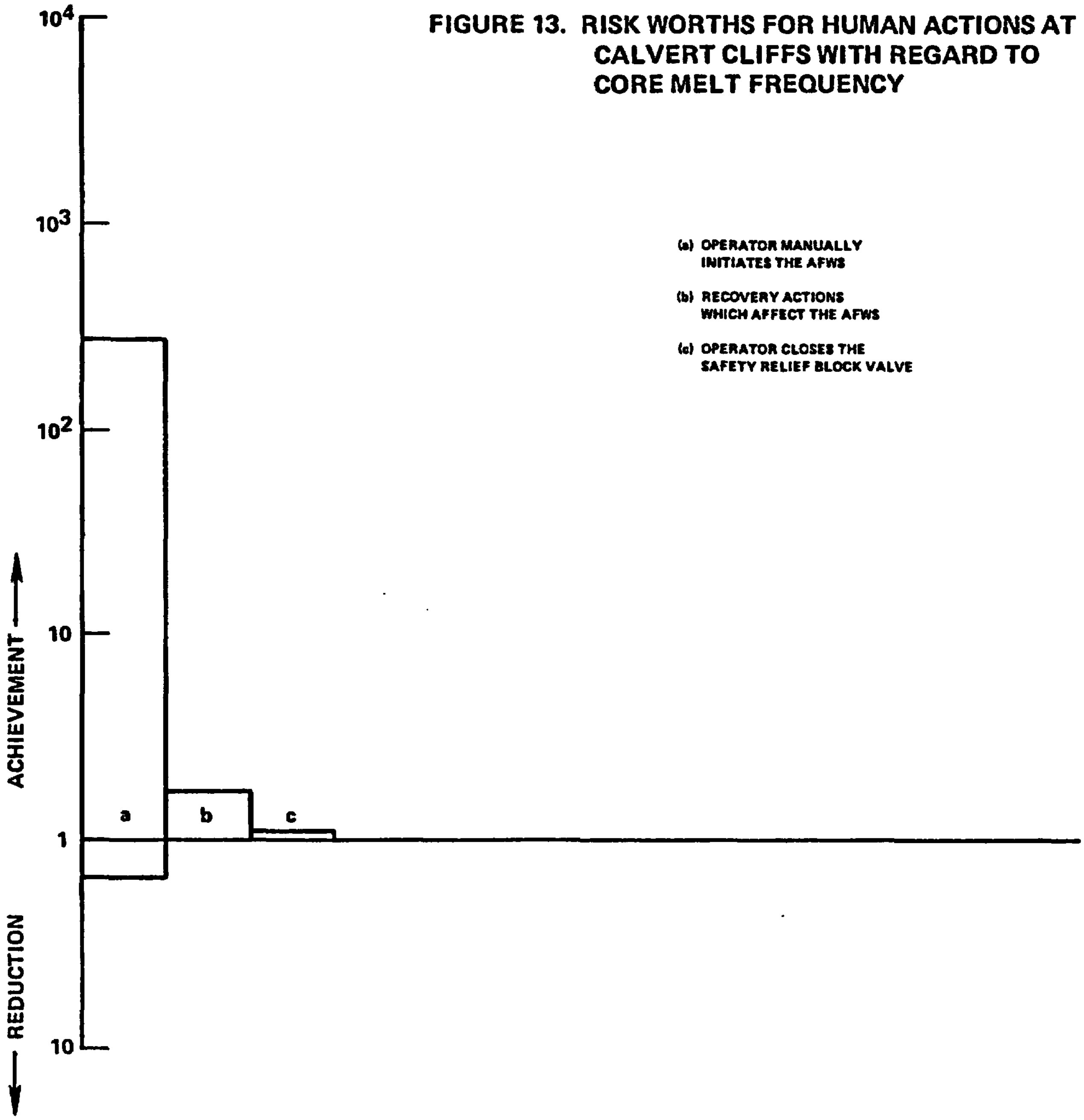


TABLE 11. RISK WORTHS FOR CALVERT CLIFFS SAFETY SYSTEMS WITH REGARD TO CORE MELT FREQUENCY

System	Risk Reduction Interval	Risk Reduction Ratio	Risk Achievement Interval	Risk Achievement Ratio
Auxiliary Feedwater	1.7×10^{-3}	6.3	0.54	270
Pressurizer Relief Valve	6.7×10^{-5}	1.0	8.4×10^{-4}	1.4
High Pressure Injection	2.9×10^{-5}	1.0	4.8×10^{-3}	3.4
Low Pressure Injection	9.9×10^{-7}	1.0	3.3×10^{-4}	1.2
Emergency Core Cooling Recirculation	4.5×10^{-5}	1.0	4.9×10^{-3}	3.4
Service Water	6.2×10^{-5}	1.0	2.5×10^{-2}	13
Emergency Power	1.7×10^{-4}	1.1	0.2	100
Reactor Protection System	6.1×10^{-5}	1.0	3.0	1500

TABLE 12. RISK WORTHS FOR CALVERT CLIFFS HUMAN ACTIONS WITH REGARD TO CORE MELT FREQUENCY

Human Action	Risk Reduction Interval	Risk Reduction Ratio	Risk Achievement Interval	Risk Achievement Ratio
Operator Manually Initiates the AFWS	5.4×10^{-4}	1.4	0.54	270
Recovery Actions Which Affect the AFWS	4.8×10^{-5}	1.0	1.2×10^{-3}	1.6
Operator Closes the Safety Relief Valve Block Valve	1.4×10^{-5}	1.0	1.3×10^{-4}	1.1

The following observations are made regarding the Calvert Cliffs results. The risk reduction ratios for reactivity control and for the emergency coolant function are small. The risk reduction potential for the heat removal function is quite large, about a factor of 30. The risk achievement worth for the reactivity control is a factor of 1500 and the risk achievement worth ratio for the heat removal function is a factor of almost 300. The emergency coolant supply function has a smaller risk achievement worth, about a factor of 3.

At the system level all of the risk reduction worth ratios are small except for the value for the auxiliary feedwater which is a factor of 6. It is interesting to compare this value with the estimated factor of 5 improvement due to the auxiliary feedwater upgrade. On the interval scale the risk reduction worths for the auxiliary feedwater system is quite high in comparison to the other systems and compared to the systems at other plants. The interval risk reduction worths for the other systems are roughly comparable to those at other plants. The interval measure is more useful for comparing plants and making value impact decisions. The ratio measure is useful in establishing the relative importance at a particular plant.

For the Calvert Cliffs systems, the risk achievement ratios show a value of over 3 orders of magnitude for the reactor protection system, approximately 2 orders of magnitude for the auxiliary feedwater and the emergency power systems, 1 order of magnitude for the service water system, and factors of 3 or less for the high pressure injection, the low pressure injection, the pressurizer relief system, and the emergency core coolant recirculation system.

The human actions identified by RSSMAP as being important to risk are shown in Table 12. The risk reduction potentials for the human activities are all small, less than a factor of 2. The risk achievement worth for the manual initiation of AFWS is also high since failure to perform the action effectively disables the auxiliary feedwater system.

Because of the importance of the auxiliary feedwater system at Calvert Cliffs, this system has been analyzed further. The system has been divided into functional groups of components such as a pump and its valves and piping. For this system, there are generally two subsystems, two feedwater sources, two pumps, and two steam supplies. One of the two in each set must function for successful system operation. The operator can be considered as a subsystem necessary for system operation. The results at the subsystem level are presented in Table 13. The ratios are shown in Figure 14. The risk reduction ratios for any one of the subsystems are small, the largest being a factor of 1.4. The risk achievement ratios for two of the subsystems, the condensate tank and supply valves and the human action are about a factor of 300. This is because failure of either could incapacitate the whole system. The risk achievement ratios for the other subsystems in the auxiliary feedwater system are about a factor of 10. Since the motor operated valves require an electric power supply, two terms have been included in Table 13 which show the risk worths of the emergency power supply to the auxiliary feedwater system valves. The risk achievement worths of these subsystems are about a factor of 3.

The subsystems can be further divided to a component level. The results of this analysis for the auxiliary feedwater system are shown in Table 14. The maximum risk reduction worth for a single component is about 1.3. Notice the risk achievement worths for any one component in a subsystem are equal to that of the entire subsystem since failure of one component would incapacitate the subsystem.

At Calvert Cliffs the system with the highest risk achievement worth was the reactor protection system. A simplified model of this system consisting of four relays and eight circuit breakers was modeled in the RSSMAP study. The risk achievement and risk reduction worths for a circuit breaker and a relay are presented in Table 15 and shown in Figure 15. Each of the other relays and circuit breakers would have the same values as the one shown. Each individual component is seen to have negligible risk reduction worth but risk achievement worths that are significant, about a factor of 5 increase on a relatively high base level risk.

TABLE 13. RISK WORTHS FOR SUBSYSTEMS IN THE AUXILIARY FEEDWATER SYSTEM AT CALVERT CLIFFS

Subsystem Description	Boolean Term	Failure Probability	Risk Reduction Interval	Risk Reduction Ratio	Risk Achievement Interval	Risk Achievement Ratio
Condensate Storage Tank, Piping, and Valves	A1	5.0×10^{-4}	2.7×10^{-4}	1.2	0.54	270
Turbine Driven Auxiliary Feed Pump #21, Piping and Valves	B1	2.9×10^{-2}	4.5×10^{-4}	1.3	1.5×10^{-2}	8.4
Turbine Driven Auxiliary Feed Pump #22, Piping and Valves	C1	2.9×10^{-2}	4.5×10^{-4}	1.3	1.5×10^{-2}	8.4
Steam Generator #21, Feedwater Supply Valves	D1	1.3×10^{-2}	2.0×10^{-4}	1.1	1.7×10^{-2}	9.6
Steam Generator #22, Feedwater Supply Valves	E1	1.3×10^{-2}	2.0×10^{-4}	1.1	1.7×10^{-2}	9.6
Steam Supply to Turbine Driven Auxiliary Feed Pumps #1	F1	1.3×10^{-2}	2.0×10^{-4}	1.1	1.7×10^{-2}	9.6
Steam Supply to Turbine Driven Auxiliary Feed Pumps #2	G1	1.3×10^{-2}	2.0×10^{-4}	1.1	1.7×10^{-2}	9.6
Power Supply to Motor Operated Valves from Diesel 12	D12	6.8×10^{-2}	9.4×10^{-5}	1.1	2.9×10^{-3}	2.5
Power Supply to Motor Operated Valves from Diesel 21	D21	8.0×10^{-2}	1.0×10^{-4}	1.1	3.0×10^{-3}	2.5
Operator Action	AFWSCM	1.0×10^{-3}	5.4×10^{-4}	1.4	0.54	270

TABLE 14. RISK WORTHS FOR COMPONENTS IN THE AUXILIARY FEEDWATER SYSTEM AT CALVERT CLIFFS

Description	Term Designation	Failure Probability	Risk Reduction Interval	Risk Reduction Ratio	Risk Achievement Interval	Risk Achievement Ratio
Subsystem A1	A1	5.0×10^{-4}	2.7×10^{-4}	1.2	0.54	270
Manual Valve	C3	2.0×10^{-4}	1.4×10^{-4}	1.1	0.54	270
Manual Valve	C4	2.0×10^{-4}	1.4×10^{-4}	1.1	0.54	270
Subsystem B1	B1	2.9×10^{-2}	4.5×10^{-4}	1.3	1.5×10^{-2}	8.4
Manual Valve	P1	2.0×10^{-4}	3.2×10^{-6}	1.0	1.5×10^{-2}	8.4
Manual Valve	P4	2.0×10^{-4}	3.2×10^{-6}	1.0	1.5×10^{-2}	8.4
Manual Valve	S6	2.0×10^{-4}	3.2×10^{-6}	1.0	1.5×10^{-2}	8.4
Check Valve	P3	1.0×10^{-4}	1.6×10^{-6}	1.0	1.5×10^{-2}	8.4
Check Valve	S5	1.0×10^{-4}	1.6×10^{-6}	1.0	1.5×10^{-2}	8.4
Turbine Pump	TP21	2.8×10^{-2}	4.4×10^{-4}	1.3	1.5×10^{-2}	8.4
Subsystem C1	C1	2.9×10^{-2}	4.5×10^{-4}	1.3	1.5×10^{-2}	8.4
Manual Valve	P2	2.0×10^{-4}	3.2×10^{-6}	1.0	1.5×10^{-2}	8.4
Manual Valve	P6	2.0×10^{-4}	3.2×10^{-6}	1.0	1.5×10^{-2}	8.4
Manual Valve	S8	2.0×10^{-4}	3.2×10^{-6}	1.0	1.5×10^{-2}	8.4
Check Valve	P5	1.0×10^{-4}	1.6×10^{-6}	1.0	1.5×10^{-2}	8.4
Check Valve	S7	1.0×10^{-4}	1.6×10^{-6}	1.0	1.5×10^{-2}	8.4
Turbine Pump	TP22	2.8×10^{-2}	4.4×10^{-4}	1.3	1.5×10^{-2}	8.4
Subsystem D1	D1	1.3×10^{-2}	2.0×10^{-4}	1.1	1.7×10^{-2}	9.6
Manual Valve	H1	2.0×10^{-4}	3.1×10^{-6}	1.0	1.7×10^{-2}	9.6
Check Valve	H5	2.0×10^{-4}	3.1×10^{-6}	1.0	1.7×10^{-2}	9.6
Control Valve	CV-4511	1.3×10^{-2}	2.0×10^{-4}	1.1	1.7×10^{-2}	9.6
Subsystem E1	E1	1.3×10^{-2}	2.0×10^{-4}	1.1	1.7×10^{-2}	9.6
Manual Valve	H2	2.0×10^{-4}	3.1×10^{-6}	1.0	1.7×10^{-2}	9.6
Check Valve	H6	2.0×10^{-4}	3.1×10^{-6}	1.0	1.7×10^{-2}	9.6
Control Valve	CV-4512	1.3×10^{-2}	2.0×10^{-4}	1.1	1.7×10^{-2}	9.6
Subsystem F1	F1	1.3×10^{-2}	2.0×10^{-4}	1.1	1.7×10^{-2}	9.6
Check Valve	S3	1.0×10^{-4}	1.5×10^{-6}	1.0	1.7×10^{-2}	9.6
Motor Operated Valve	MOV-4071	1.3×10^{-2}	2.0×10^{-4}	1.1	1.7×10^{-2}	9.6
Subsystem G1	G1	1.3×10^{-2}	2.0×10^{-4}	1.1	1.7×10^{-2}	9.8
Check Valve	S4	1.0×10^{-4}	1.6×10^{-6}	1.0	1.7×10^{-2}	9.8
Motor Operated	MOV-4070	1.3×10^{-2}	2.0×10^{-4}	1.1	1.7×10^{-2}	9.8

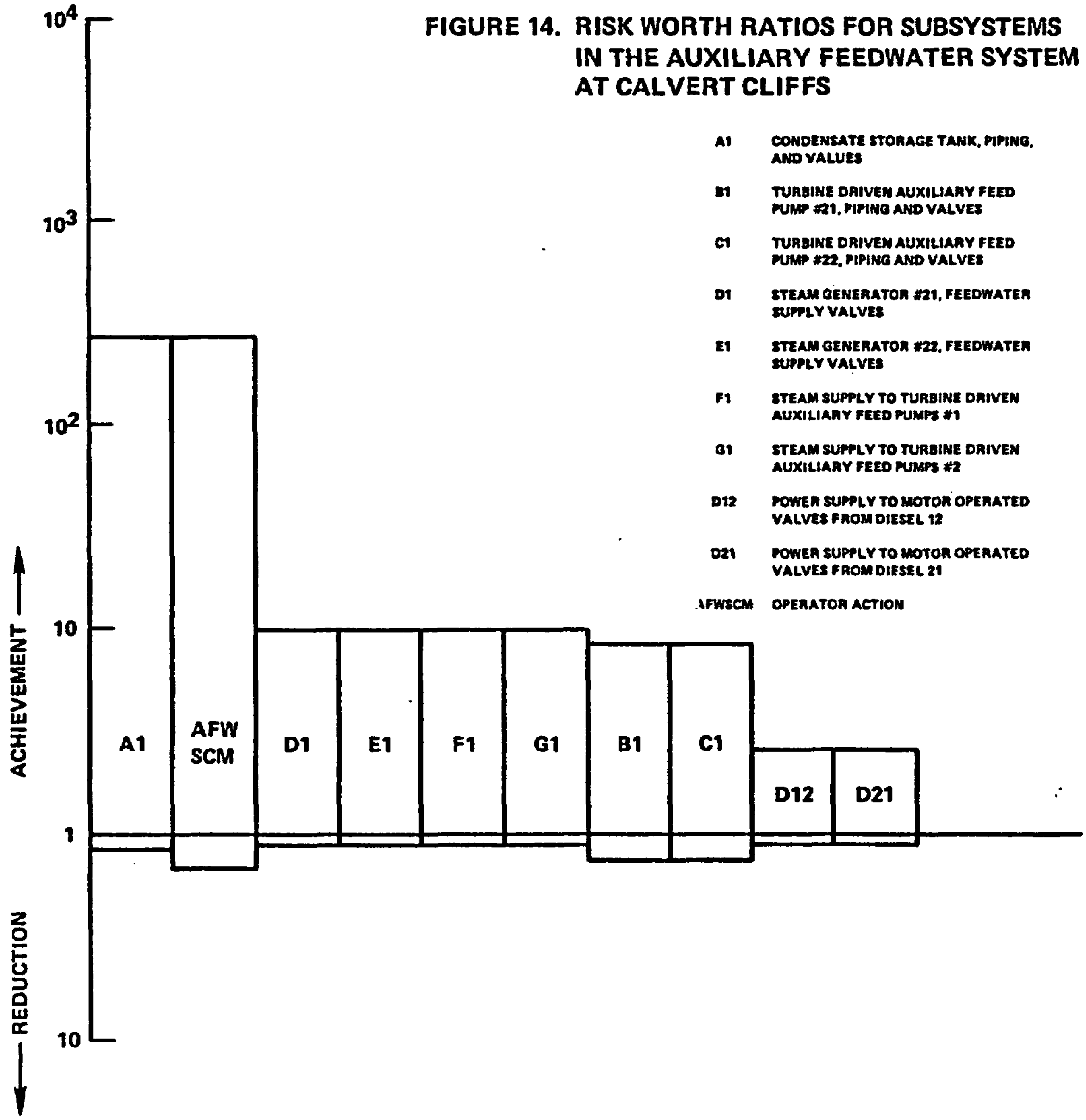


FIGURE 14. RISK WORTH RATIOS FOR SUBSYSTEMS IN THE AUXILIARY FEEDWATER SYSTEM AT CALVERT CLIFFS

FIGURE 15. RISK WORTH RATIOS FOR COMPONENTS OF THE REACTOR PROTECTION SYSTEM AT CALVERT CLIFFS

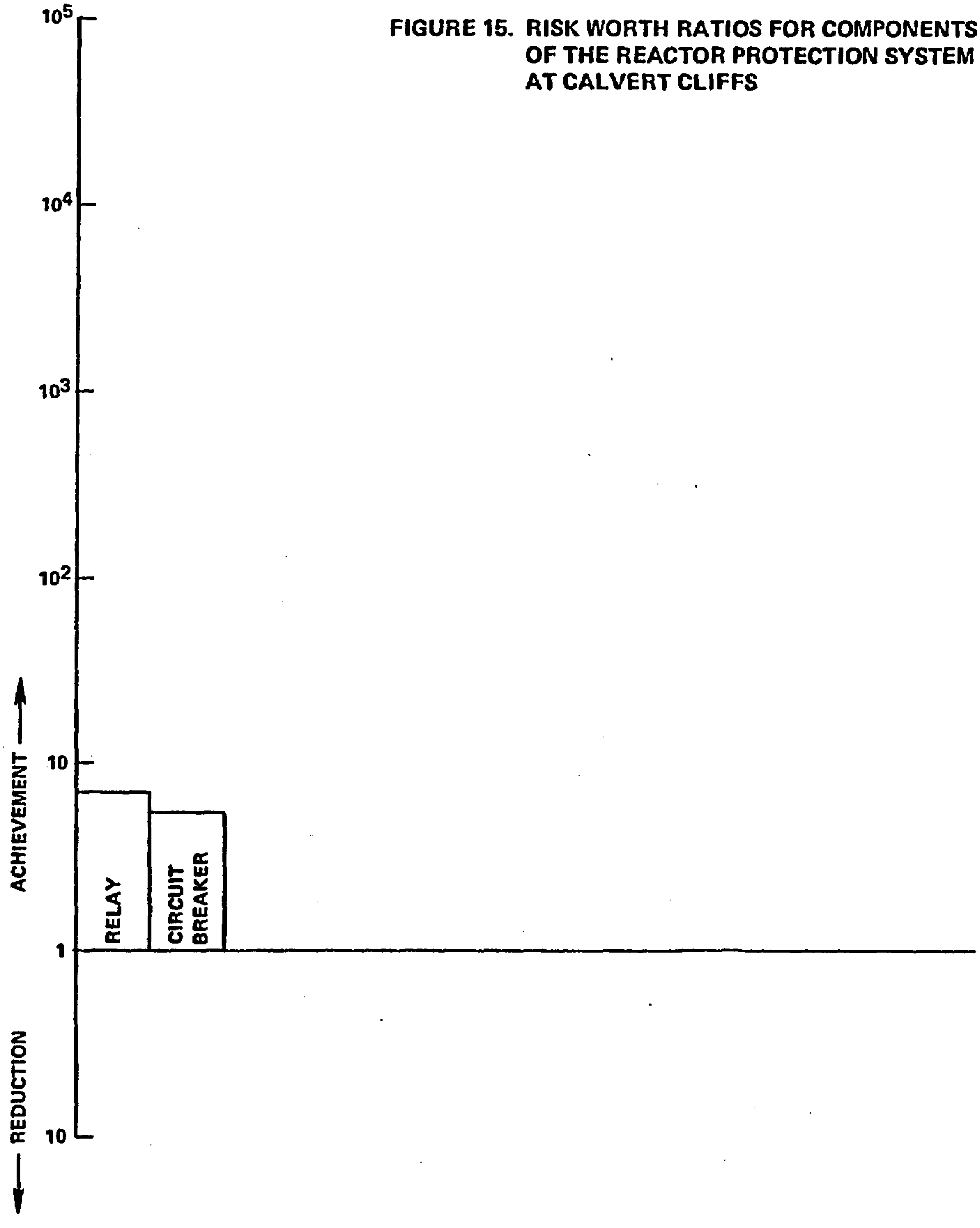


TABLE 15. RISK WORTHS FOR COMPONENTS OF THE REACTOR PROTECTION SYSTEM AT CALVERT CLIFFS

Component	Risk Reduction		Risk Achievement	
	Interval	Ratio	Interval	Ratio
Circuit Breaker (1 of 8)	9×10^{-6}	1.0	9.0×10^{-3}	5.5
Relay (1 of 4)	0	1.0	1.2×10^{-2}	7.0

8.4 Grand Gulf

The risk worths for the safety functions at Grand Gulf are presented in Table 16 and the ratios are displayed graphically in Figure 16. The risk worths at the system level are presented in Table 17. The risk worth ratios for the systems are shown in Figure 17. The important human actions identified in RSSMAP are presented in Table 18 and shown in Figure 18.

TABLE 16. RISK WORTHS FOR GRAND GULF SAFETY FUNCTIONS WITH REGARD TO CORE MELT FREQUENCY

Function	Risk Reduction		Risk Achievement	
	Interval	Ratio	Interval	Ratio
Reactivity Control	5.4×10^{-6}	1.2	7.0	$2.0 \times 10^{+5}$
Provide Emergency Coolant to Core	2.3×10^{-6}	1.1	.72	$2.0 \times 10^{+4}$
Transfer Heat to Ultimate Sink (not including main power conversion)	2.8×10^{-5}	4.7	5.4×10^{-2}	1500

FIGURE 16. RISK WORTH RATIOS FOR GRAND GULF SAFETY FUNCTIONS WITH REGARD TO CORE MELT FREQUENCY

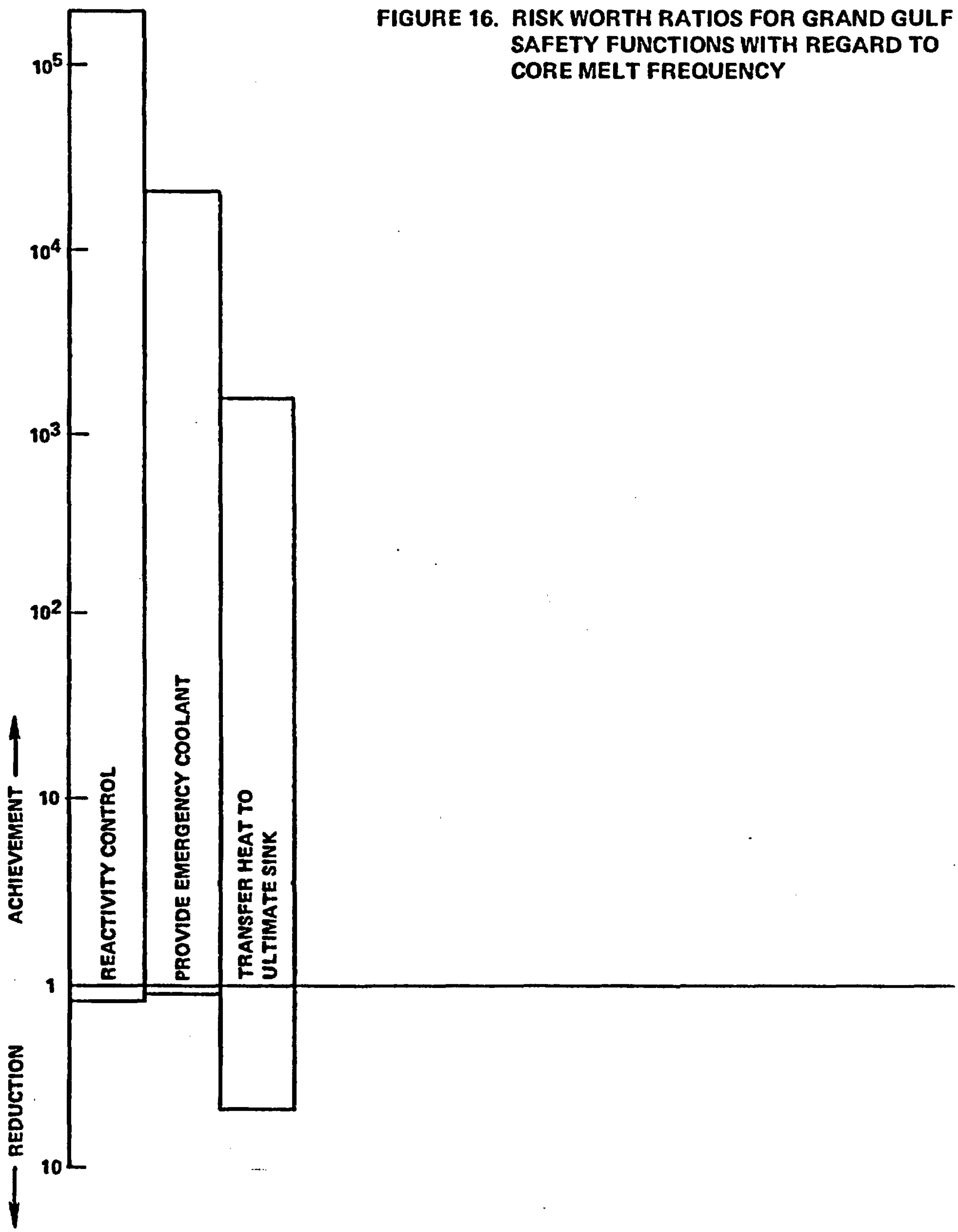


FIGURE 17. RISK WORTH RATIOS FOR GRAND GULF SAFETY SYSTEMS WITH REGARD TO CORE MELT FREQUENCY

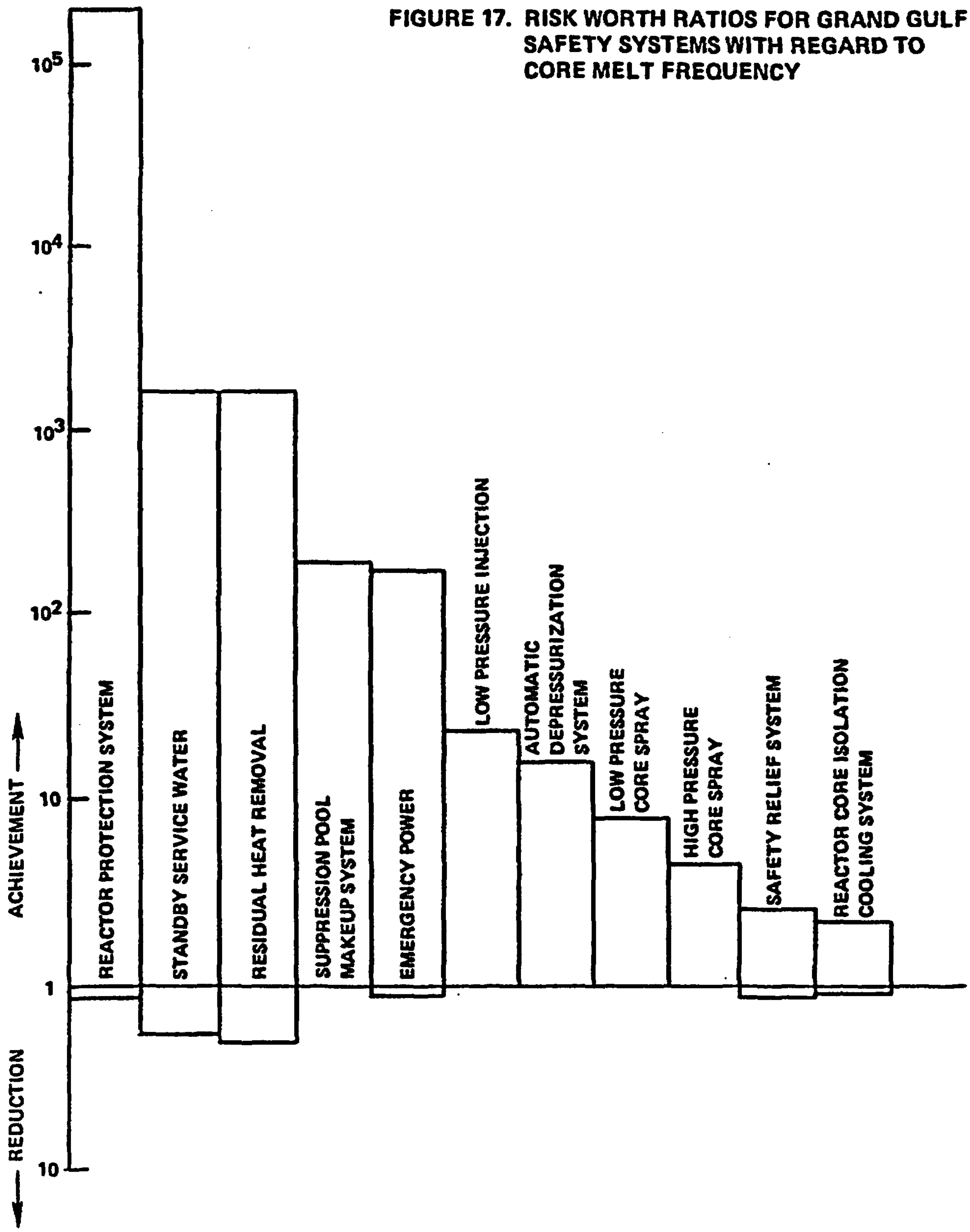


FIGURE 18. RISK WORTH RATIOS FOR IDENTIFIED HUMAN ACTIONS AT GRAND GULF

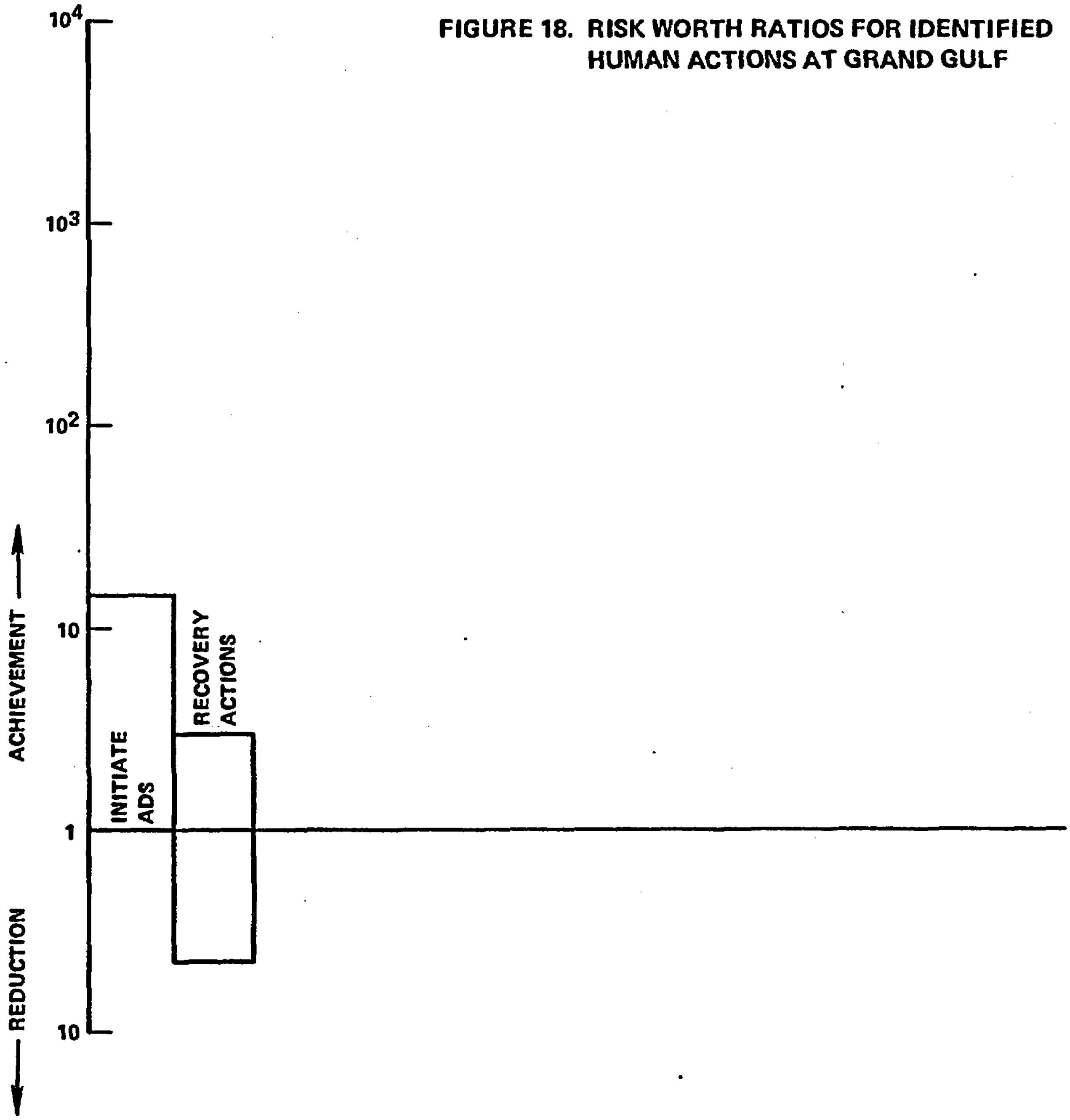


TABLE 17. RISK WORTHS FOR GRAND GULF SAFETY SYSTEMS WITH REGARD TO CORE MELT FREQUENCY

System	Risk Reduction Interval	Risk Reduction Ratio	Risk Achievement Interval	Risk Achievement Ratio
Failure of a Safety/Relief Valve to Reseat	6.1×10^{-6}	1.2	5.5×10^{-5}	2.5
Supression Pool Makeup System	4.3×10^{-7}	1.0	6.8×10^{-3}	190
AC Onsite Power	7.1×10^{-6}	1.2	6.1×10^{-3}	170
Standby Service Water	1.7×10^{-5}	1.9	5.4×10^{-2}	1500
Low Pressure Coolant Injection System	7.2×10^{-7}	1.0	7.9×10^{-4}	23
Residual Heat Removal System	1.8×10^{-5}	2.0	5.4×10^{-2}	1500
High Pressure Core Spray	1.1×10^{-6}	1.0	1.2×10^{-4}	4.4
Low Pressure Core Spray	5.2×10^{-7}	1.0	2.4×10^{-4}	7.6
Reactor Core Isolation Cooling System	4.2×10^{-6}	1.1	4.2×10^{-5}	2.2
Reactor Protection System	5.4×10^{-6}	1.2	7.0	2.0×10^{5}
Automatic Depressurization System	7.3×10^{-7}	1.0	4.8×10^{-4}	14

TABLE 18. RISK WORTHS FOR IDENTIFIED HUMAN ACTIONS AT GRAND GULF WITH REGARD TO CORE MELT FREQUENCY

Action	Risk Reduction Interval	Risk Reduction Ratio	Risk Achievement Interval	Risk Achievement Ratio
Operator Initiation of Automatic Depressurization System	7.3×10^{-7}	1.0	4.8×10^{-4}	14
Recovery	2.8×10^{-5}	4.5	1.0×10^{-4}	3.0

At the functional level for the Grand Gulf plant the maximum risk reduction potential is a factor of 5 for the heat removal function. The other functions have small risk reduction potential. The risk achievement worths for the safety functions are all large, with reactivity control being an order of magnitude more important than emergency cooling which in turn is an order of magnitude more important than heat transfer.

The reactivity control function has a risk achievement ratio of 5 orders of magnitude. This value is extremely high primarily because at Grand Gulf a failure to scram was assumed to lead directly to core melt. The emergency coolant supply function has a risk achievement worth of 4 orders of magnitude. This is also very high and is primarily due to the high incidence of transient induced LOCAs predicted for the Grand Gulf RSSMAP study. The risk achievement worth of the heat removal function is about 3 orders of magnitude.

At the system level the residual heat removal system and the standby service water system have risk reduction worths of about a factor of 2. All other systems have risk reduction worths less than 1.2. The risk achievement worth for the reactor protection system is the highest with a ratio over 5 orders of magnitude. The residual heat removal system and the standby service water system have risk achievement ratios of 1500. Both of these systems are necessary for long term heat removal. The suppression pool makeup system and the emergency power system have risk achievement ratios of about 200. The rest of the system are designed to provide emergency cooling water to the core and have risk achievement ratios that range from a factor of 2 to a factor of 20. Notice the risk achievement ratio for any one system is much lower than for the emergency core cooling function because any one of several systems can accomplish the functional requirements.

The Grand Gulf study identified two human actions that were important to risk. The first involved initiation of the automatic depressurization system. The risk reduction worth for this action was small while the risk achievement worth was a factor of about 10. The other action involved maintenance actions to recover failed systems during the time when the supression pool is heated up. Based on the analysis done for RSSMAP, a risk reduction factor of 5 was possible if the maintenance teams could identify and repair the systems every time and a factor of 3 increase in risk would occur if the repair were done incorrectly.

8.5 Comparisons

This section briefly compares the results of the risk worth analyses for the four RSSMAP plants. This comparison provides insights regarding the features that are important and also points out areas where modeling assumptions may be important. A comparison of the base case risk level of core melt frequency as calculated by RSSMAP for the four plants is shown on Table 19. This table shows three of the plants have approximately equal core melt frequencies (to within a factor of two) whereas the Calvert Cliffs plant has a core melt frequency of a factor of 25 higher than any other plant analyzed. This indicates that interval values are useful for interplant comparisons of feature worths since they take into account the different base (nominal) risk levels whereas the ratio worths do not.

TABLE 19. CORE MELT FREQUENCIES OF THE FOUR RSSMAP PLANTS

Plant	Core Melt Frequency
Calvert Cliffs	2.0×10^{-3}
Oconee	8.2×10^{-5}
Sequoyah	5.6×10^{-5}
Grand Gulf	3.6×10^{-5}

The risk worths of the safety functions for the four plants are given in Tables 20, 21, and 22. All the worths are calculated with regard to core melt frequency. Table 20 shows the risk worths for the reactivity control function at the four plants. On an interval basis Calvert Cliffs has the highest risk reduction worth, which is about an order of magnitude higher than the other plants.

TABLE 20. RISK WORTHS FOR THE REACTIVITY CONTROL FUNCTION AT THE FOUR RSSMAP PLANTS

Plant	Risk Reduction		Risk Achievement	
	Interval	Ratio	Interval	Ratio
Grand Gulf	5.4×10^{-6}	1.2	7.0	2.0×10^{5}
Calvert Cliffs	6.0×10^{-5}	1.0	3.0	1500
Oconee	7.8×10^{-6}	1.1	.32	4100
Sequoyah	2.5×10^{-6}	1.1	7.1×10^{-2}	1200

The risk achievement worth of the reactivity control function has different prioritizations across plants when interval values are used as compared to ratio values. When interval values are used, which account for the different baseline core melt frequencies, the worth at Grand Gulf is about a factor of 2 higher than that at Calvert Cliffs which, in turn, is about an order of magnitude higher than the worth at Oconee. These across plant comparisons are useful as a guide to mandating modifications or in allocating resources among different plants. They are also useful for identifying patterns in the worths.

Table 21 shows the risk worths for the emergency core cooling function at the four plants. The risk reduction worths for the three PWRs (Calvert Cliffs, Oconee, and Sequoyah) are approximately equal on an interval scale. The risk reduction worth at Grand Gulf is about an order of magnitude less. The difference in emergency core cooling reduction worths may be attributed to the fact that there are several systems which can provide core cooling at Grand Gulf in the event of a loss of coolant. This redundancy of systems provides a near optimum function, thus a low risk reduction worth.

TABLE 21. RISK WORTHS FOR THE EMERGENCY CORE COOLING FUNCTION AT THE FOUR RSSMAP PLANTS

Plant	Risk Reduction		Risk Achievement	
	Interval	Ratio	Interval	Ratio
Grand Gulf	2.3×10^{-6}	1.1	.72	2.0×10^{4}
Calvert Cliffs	7.4×10^{-5}	1.0	3.3×10^{-3}	2.6
Oconee	4.3×10^{-5}	2.5	3.4×10^{-3}	48
Sequoyah	5.3×10^{-5}	7.0	2.8×10^{-3}	50

The risk achievement worth for the emergency core cooling function is about the same, on an interval scale for all three PWRs. The worth at the BWR (Grand Gulf) is approximately two orders of magnitude higher than for the

PWRs. This is due to the greater number of safety relief valves which could fail at a BWR thereby requiring the coolant function. This also may reflect some pessimistic modeling assumptions regarding the reliability of these valves. If a higher reliability was used for these valves, a lower frequency of transient induced LOCA's would be predicted resulting in a lower risk achievement worth for this function at this plant.

Table 22 shows the risk worths for the heat removal function at the four plants. On an interval scale, the risk reduction worth for Calvert Cliffs stands out as being very high, approximately two orders of magnitude higher than the other plants (before modifications to the auxiliary feedwater system at Calvert Cliffs).

TABLE 22. RISK WORTHS FOR THE HEAT REMOVAL FUNCTION AT THE FOUR RSSMAP PLANTS

Plant	Risk Reduction		Risk Achievement	
	Inverval	Ratio	Interval	Ratio
Calvert Cliffs	1.9×10^{-3}	28	.54	270
Oconee	2.0×10^{-5}	1.4	.54	7500
Sequoyah	3.0×10^{-6}	1.1	.11	2000
Grand Gulf	2.8×10^{-5}	4.7	5.4×10^{-2}	1500

The risk achievement worths for the heat removal function consider only the standby heat removal systems such as the auxiliary feedwater and the residual heat removal systems but do not consider the main power conversion system or the suppression pool as being unavailable. The risk achievement worths are equal for Calvert Cliffs and Oconee and are somewhat lower for Sequoyah because of different modeling assumptions. The risk achievement worth at the BWR (Grand Gulf) is the lowest because of the additional recovery time afforded by the suppression pool's long heatup period.

At the system level the following observations are made when comparing the plants. Referring to the risk worths on Tables 4, 7, 11, and 17 it is seen that the risk reduction worths for the systems at Calvert Cliffs are generally higher than the systems at other plants. The auxiliary feedwater and emergency power are two orders of magnitude higher while the service water, pressure relief system and the reactor protection system are one order of magnitude higher. The high pressure injection, low pressure injection, and emergency core cooling recirculation systems have values that are comparable to the other plants. For the other three plants (Oconee, Sequoyah, Grand Gulf) the risk reduction worths are generally comparable. At all three of these plants the systems providing long term cooling, the emergency core cooling recirculation, and the residual heat removal systems have the highest risk reduction worths.

The risk achievement worths for the four plants at the system level have a wide range of values. The values for all plants are generally considerably higher than the risk reduction worths. For some systems there is considerable variation in the risk achievement worths among different plants. This reflects design differences in the plants but may also be due in part to different modeling assumptions. For the auxiliary feedwater Calvert Cliffs has the highest risk achievement worth. Because of the "feed and bleed" cooling mode option at Oconee the risk achievement worth is an order of magnitude lower.

The risk achievement worths for the core cooling systems such as the high pressure injection, the low pressure injection, the emergency core cooling recirculation, the high pressure core spray, and the low pressure core spray have comparable values at all the plants. The Oconee plant has the highest risk achievement value for standby service water since the auxiliary feedwater and the core cooling water will fail if this system is failed. The Calvert Cliffs plant has the highest risk achievement value for emergency power in part because the auxiliary feedwater at Calvert Cliffs depends on electric power.

The human actions identified as being important to risk estimates are generally quite different at each of the four plants, as can be seen on Tables 5, 8, 12, and 18. The highest risk reduction worth was for operator initiation of the auxiliary feedwater system at Calvert Cliffs. The risk achievement worths for human actions are consistently higher than the risk reduction worths. Operator initiation of the auxiliary feedwater also had the highest risk achievement worth.

8.6 Risk Impact Curves

As discussed in Section 6.0, to complement the risk worths, risk impact curves can be constructed. The construction of the risk impact curve is straightforward for systems and components. The impact curves for the reactor protection system at Grand Gulf and the auxiliary feedwater system at Calvert Cliffs are shown in Figures 19 and 20, with core melt frequency as the risk measure. These systems have the highest risk reduction worth and the highest risk achievement worth, respectively, for core melt frequency.

The risk impact curve for the reactor protection system at Grand Gulf (Figure 19) shows the relative failure probability of the system on the x-axis. A log scale is used to display the wide range of values. The y-axis also uses a log scale and displays the relative risk of core melt frequency as a function of the failure probability.

Notice the risk reduction worth and the risk achievement worth are seen on this curve as described in Section 6.0. At the far left side of the curve the failure probability is near zero and the reciprocal of the risk reduction worth is reached. As the relative failure probability is increased to 1 the relative risk also increases to 1. The relative risk continues to increase as the relative failure probability is increased until the failure probability equals 1. At this level the risk achievement worth is reached and the curve flattens out. The risk impact curve for the auxiliary feedwater system at Calvert Cliffs (Figure 20) shows similar behavior.

Risk impact curves can be adopted to aid cost-benefit decision making. For example, the interval change in expected core melt frequency can be converted to a change in expected benefits using the results of the RSSMAP consequence analysis and appropriate consequence conversion factors. If, for example, a value of $1000/manrem is used as a measure of benefit, the change in manrem can be readily converted to dollars. The curve of risk reduction $R - R_0$ in terms of dollars benefitted is then plotted versus the probability

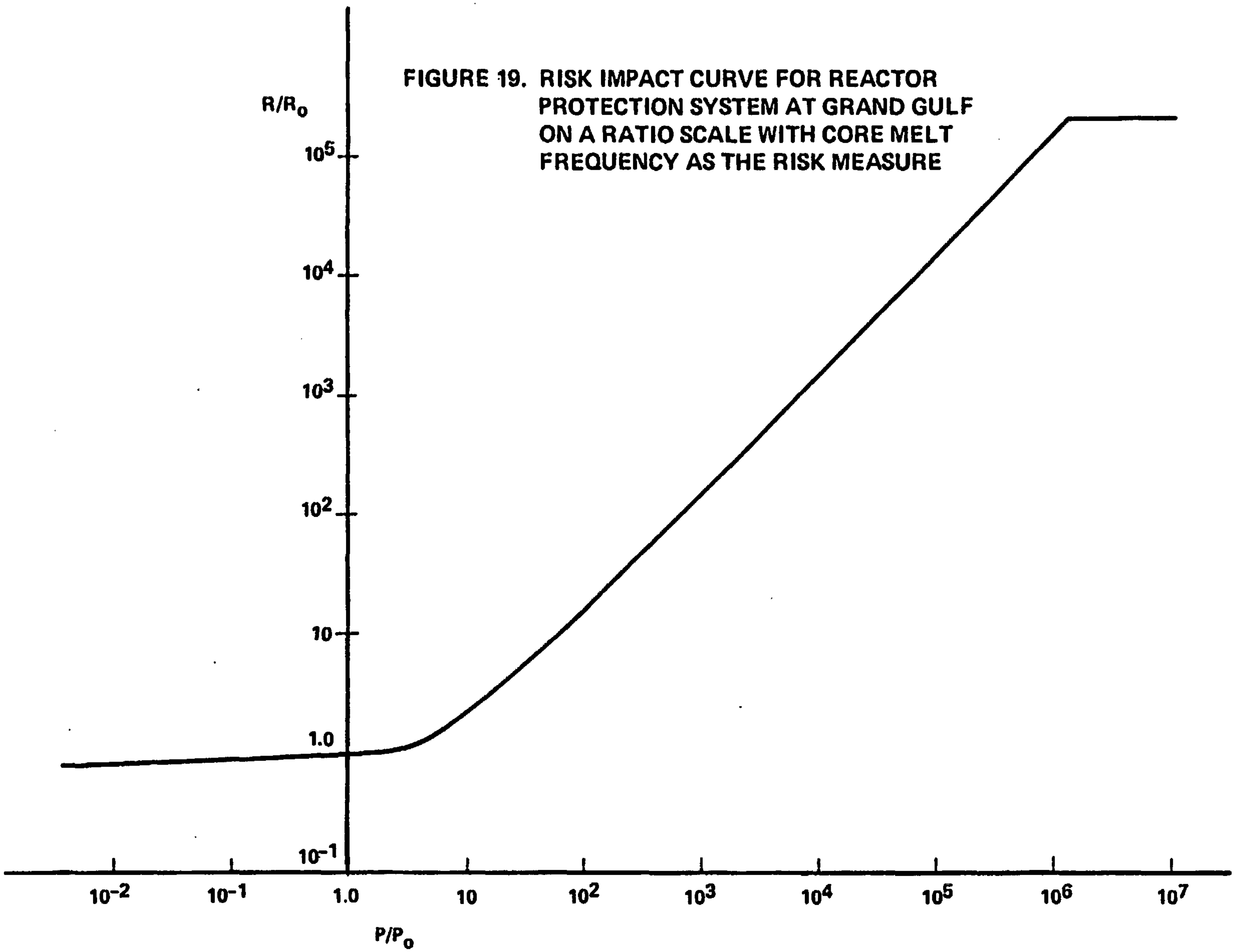
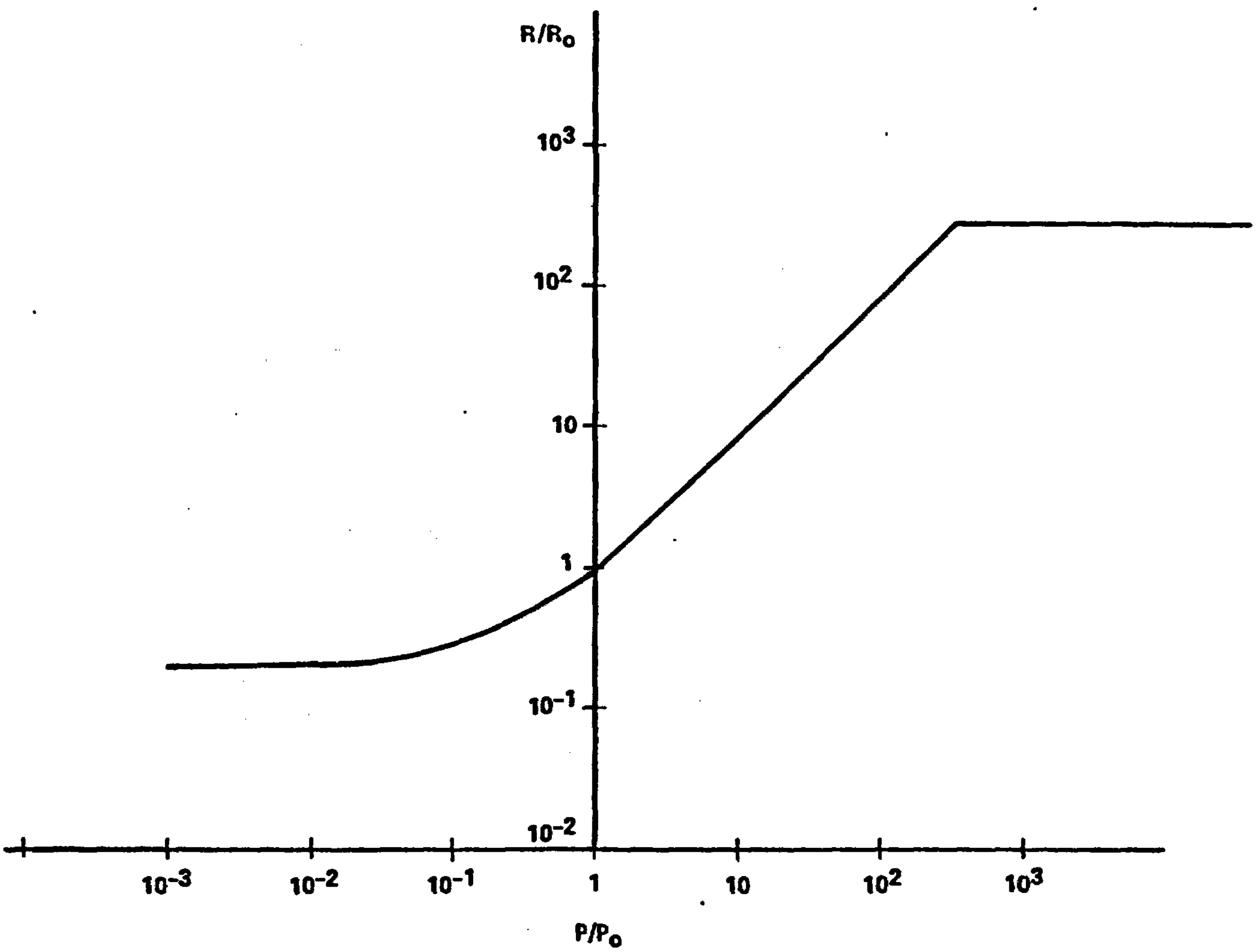


FIGURE 19. RISK IMPACT CURVE FOR REACTOR PROTECTION SYSTEM AT GRAND GULF ON A RATIO SCALE WITH CORE MELT FREQUENCY AS THE RISK MEASURE

FIGURE 20. RISK IMPACT CURVE FOR AUXILIARY FEEDWATER SYSTEM AT CALVERT CLIFFS ON A RATIO SCALE WITH CORE MELT FREQUENCY AS THE RISK MEASURE



decrease $P - P_o$ of the component or system. If the cost of the probability decrease is more than the dollar benefit then the modification is not cost effective. The region above the curve is thus the "not cost effective" region and the region below the curve is the cost effective region. These regions can then be used to aid decision making.

Figure 21 is a general illustration of a cost-effectiveness type curve. In the figure, risk reduction $R_o - R$ and failure probability reduction are plotted. To evaluate a proposed modification to a system, for example, the resulting impact on the system failure probability $P_o - P$ can be identified on the x-axis. If the cost of the modification is within the cost effective region then the modification is indicated to be cost effective. Otherwise it is not. Even with uncertainties these kinds of curves can give useful information. For example, from Figure 21 it is seen that any modification having cost above B_{max} is not cost effective regardless of the risk reduction.

Figures 22 and 23 show the calculated cost effectiveness curves for the two systems analyzed earlier in this section. The consequence factors for manrem shown in Section 7 were used along with the conversion factor of $1000 per manrem.

For the reactor protection system at Grand Gulf, shown in Figure 22, the maximum benefit is seen to be less than $12,000 per year. Costs above this level translated to a total plant lifetime would not be cost effective. Achieving the maximum benefit would require reducing the system failure probability to near zero, which may be impossible to accomplish. Smaller incremental improvements would have smaller benefits as indicated on the curve.

The auxiliary feedwater system at Calvert Cliffs had the highest risk reduction worth of any system analyzed. This is reflected by the high benefit values on the cost benefit curve shown in Figure 23. Benefits of almost $2,000,000 per year are predicted by improving the present system. The effect of the planned changes to the system described in the RSSMAP study are approximately indicated on the curve by P_1. About 90 percent of the potential improvement is realized by these changes.

FIGURE 21. GENERAL COST EFFECTIVENESS CURVE

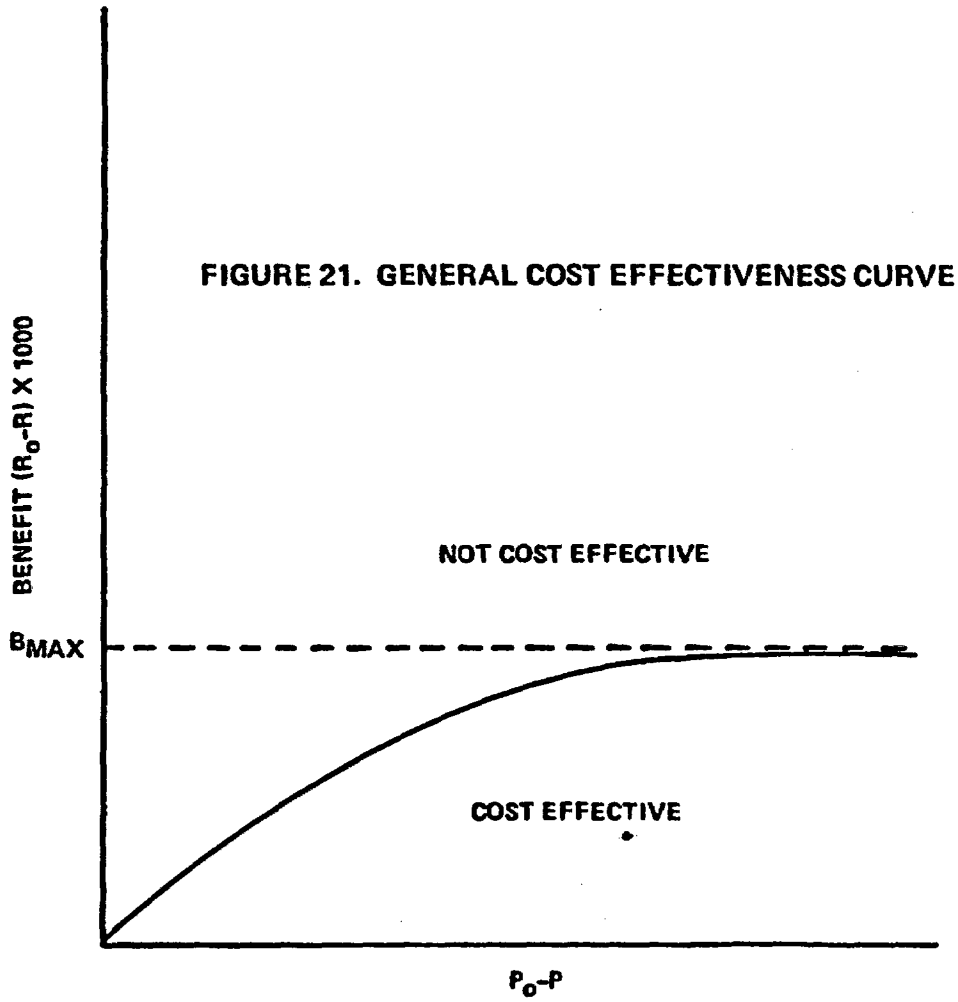
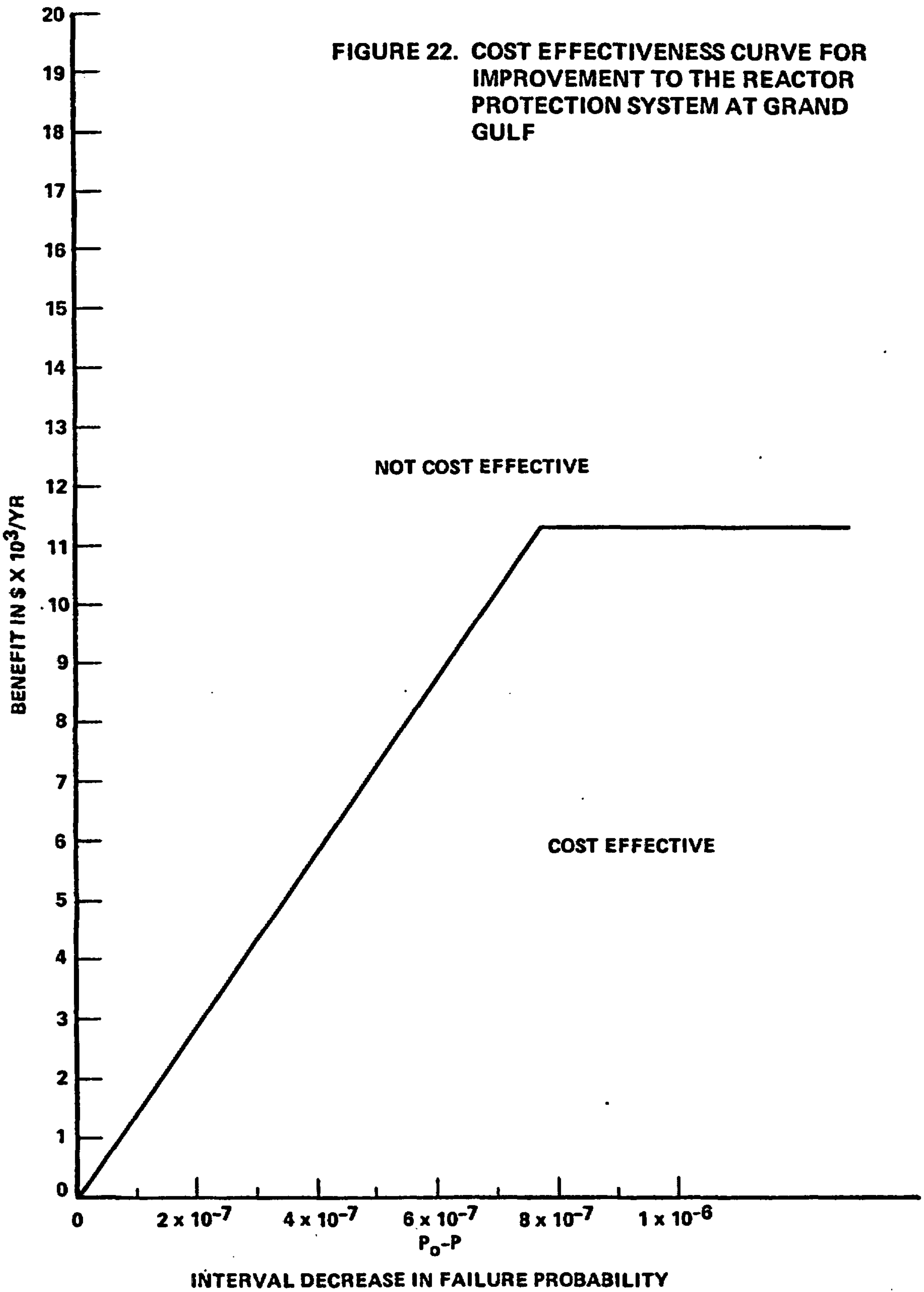


FIGURE 22. COST EFFECTIVENESS CURVE FOR IMPROVEMENT TO THE REACTOR PROTECTION SYSTEM AT GRAND GULF



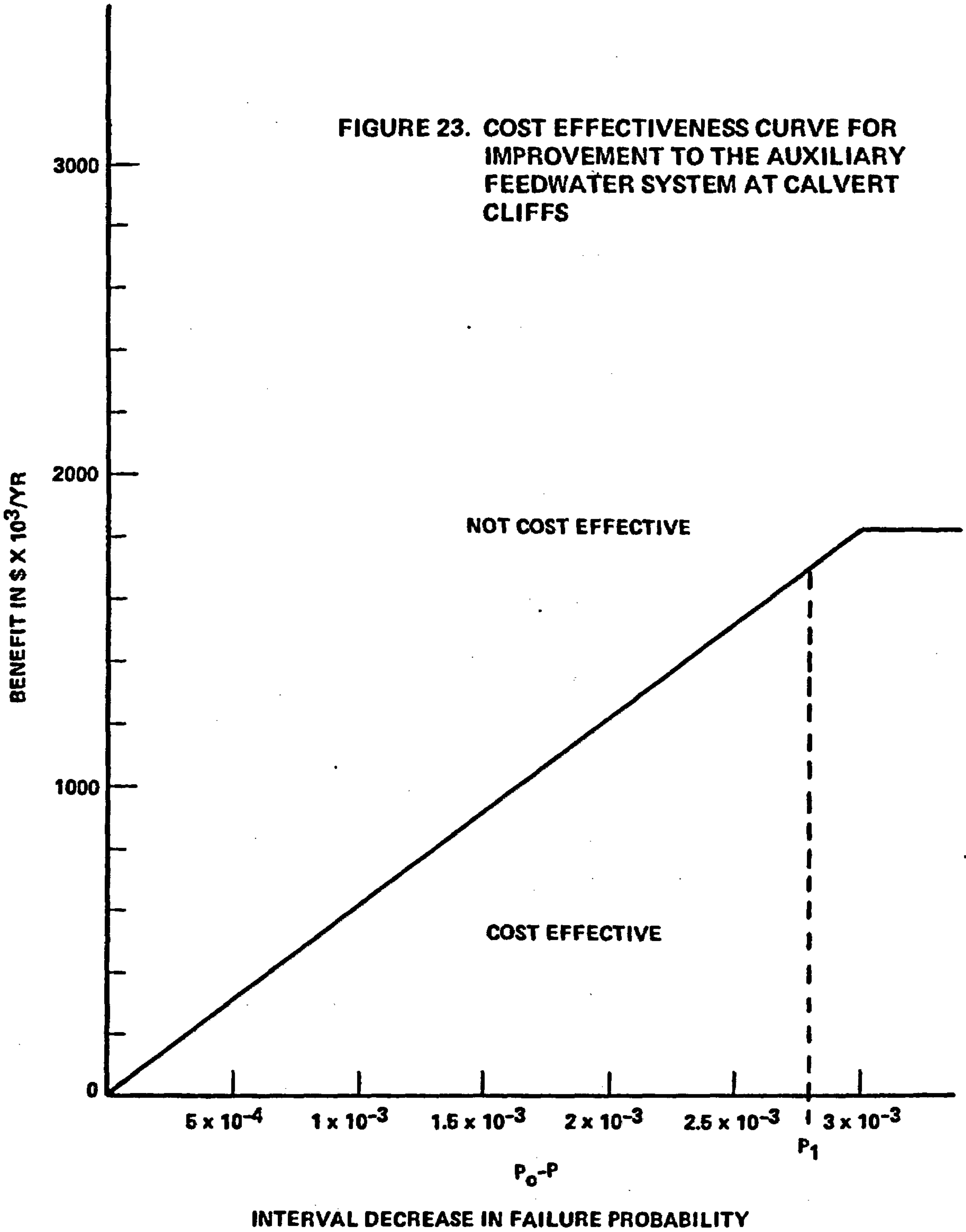


FIGURE 23. COST EFFECTIVENESS CURVE FOR IMPROVEMENT TO THE AUXILIARY FEEDWATER SYSTEM AT CALVERT CLIFFS

9.0 CONTAINMENT ANALYSIS

In this section risk worth measures and sensitivity studies are applied to the containment in order to investigate its risk importance. In Section 9.1 the risk worths for the four RSSMAP plants are calculated. In Section 9.2 the importance of containment design is investigated by assuming different containments are placed on one plant and calculating the risk worths for each containment design. Section 9.3 examines the importance of the assumed mean failure pressure to risk estimates at one plant. Section 9.4 defines two measures of containment reliability and evaluates the RSSMAP designs using these measures. For the risk worth evaluations, the risk measures calculated are expected manrem and expected acute fatalities. (Core melt frequency is not a useful measure for calculating importances of consequence mitigating features since it is assumed the containment has no effect on core melt frequency.)

9.1 Risk Worths of RSSMAP Containments

The risk worth calculations involve determining the decreased risk level with the containment assumed optimized and the risk level with no containment and comparing to the risk level predicted by RSSMAP.

The containment worth ratios for the four plants are shown in Table 23. The risk achievement ratios indicate the containment presently reduces dose by a factor of about 3 and reduces early fatalities by a factor of 10. The risk reduction ratios indicate that acute fatalities could be reduced to essentially zero (giving a risk reduction ratio of infinity) for those plants not having the V sequence (releases which bypass containment). For the plants where the V sequence is important, acute fatalities could at most be reduced by a factor of ~ 10. For those plants without V, manrem could be reduced by a factor of $\sim 10^3$ if containment were optimized; for plants with V, a factor of ~ 10 is the most that dose can be reduced. The risk worths of the four containments are graphed on Figure 24 using manrem as the risk measure and neglecting the V sequence.

TABLE 23. CONTAINMENT RISK WORTHS

Plant		Risk Reduction Worth: Interval Manrem	Risk Reduction Worth: Interval Acute Fatalities	Risk Reduction Worth: Ratio Manrem	Risk Reduction Worth: Ratio Acute Fatalities	Risk Achievement Worth: Interval Manrem	Risk Achievement Worth: Interval Acute Fatalities	Risk Achievement Worth: Ratio Manrem	Risk Achievement Worth: Ratio Acute Fatalities
Sequoyah	with V	65.6	3.0×10^{-3}	12.5	11.8	79.0	2.7×10^{-2}	2.12	9.09
	without V	65.6	3.0×10^{-3}	1726.	∞	79.0	2.7×10^{-2}	2.21	9.93
Oconee	with V	38.2	2.0×10^{-3}	9.7	10.0	107.4	2.7×10^{-2}	3.53	13.4
	without V	38.2	2.0×10^{-3}	888.	∞	107.4	2.7×10^{-2}	3.82	14.6
Calvert Cliffs		1710.	9.3×10^{-2}	1657.	∞	2388.	7.1×10^{-1}	2.40	8.69
Grand Gulf		80.8	2.0×10^{-3}	2886.	∞	27.6	1.9×10^{-2}	1.34	10.6

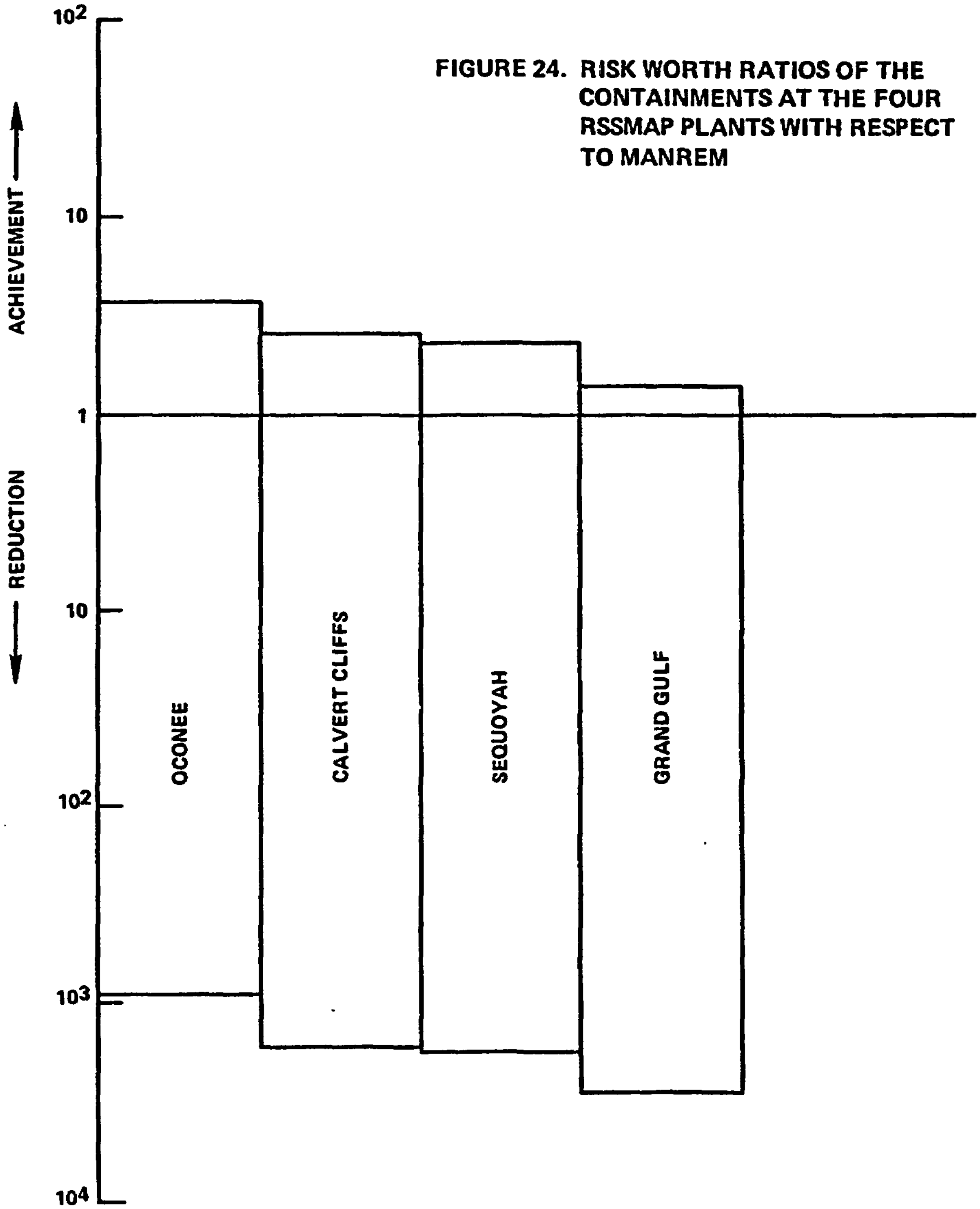


FIGURE 24. RISK WORTH RATIOS OF THE CONTAINMENTS AT THE FOUR RSSMAP PLANTS WITH RESPECT TO MANREM

It is interesting to note that the ratio measures of risk worth are independent of the core melt frequency while the interval values are a function of the magnitude of the core melt frequency. The ratio worths thus tend to isolate the effectiveness of containment whereas the interval worths are useful for decisions involving the risk level or cost-benefit comparisons.

For the above evaluations, the decreased risk level with the containment optimized is calculated by assuming the containment is capable of withstanding all threats to containment integrity, the containment never fails to isolate, and the sprays always operate. Since these assumptions are equivalent to a PWR Category 7 release, the consequence factors for that category are applied to the total core melt frequency to determine the risk level with an optimized containment. The decreased risk levels calculated for the four RSSMAP plants are shown in Table 24. These values represent the lower limit of risk which could be obtained from an optimized or "perfect" containment. Other considerations may introduce limits to the containment's reliability resulting in a somewhat higher risk.

For two of the plants, the V sequence was determined to be important to the present risk level. Since the containment is bypassed for this sequence, the containment has no effect on the V sequence. The risk level, therefore, cannot be reduced below this level no matter how effective the containment. If the risk is to be further reduced, the frequency of the V sequence must be reduced. To show the impact of the V sequence, the risk worths have been calculated with and without the V sequence for the plants where this sequence was considered important.

For the evaluation of the risk achievement worths, the increased risk level from a failed containment or a containment that was not installed was determined by assuming there was no containment. With no containment there would be no fission product removal mechanisms such as sprays, filters, or deposition on walls and floors. With this assumption, all of the fission products released from the primary system are released directly to the environment. If it is further assumed that there is no deposition within the primary system, all of the fission products released from the fuel would be released to the environment. The source assumed is shown in Table 25. The source is equivalent to the WASH-1400 source release from the fuel. These

TABLE 24. CONTAINMENT ANALYSIS

Plant	Base Case Man Rem	Base Case Acute Fatalities	Risk Without Containment Man Rem	Risk Without Containment Acute Fatalities	With Optimized Containment Man Rem	With Optimized Containment Acute Fatalities
OCONEE with V	42.5	2.2×10^{-3}	150	0.0294	4.4	2.2×10^{-4}
without V	38.2	2.0×10^{-3}	146	0.0292	0.043	0.
SEQUOYAH with V	71.3	3.3×10^{-3}	151	0.0300	5.7	2.8×10^{-4}
without V	65.6	3.0×10^{-3}	145	0.0298	0.038	0.
CALVERT CLIFFS	1710	0.093	4099	0.804	1.03	0.
GRAND GULF	80.8	2.0×10^{-3}	108	0.0212	0.028	0.

TABLE 25. TOTAL SOURCE RELEASE

Fission Product Group	Fraction Released
Xe	1.0
I	1.0
Cs	1.0
Te	1.0
Ba	0.11
Ru	0.08
La	0.013
Consequences for 1120 MWe Plant	
Expected Man Rem	2.7×10^{6}
Expected Early Fatalities	530

release fractions were input to the CRAC code to determine consequence factors which are shown in Table 25. The expected risk with these assumptions for each plant is shown in Table 24. The assumption of no deposition in the primary system causes the consequences to be overestimated. Ongoing analyses indicates the retention factors within the primary system can be significant for some isotopes under certain conditions. This reduction of the source term due to this mechanism would lead to a lower environmental release and correspondingly lower health effects. A reduced source term would affect the base case risk similarly. Future analyses should address this issue as results become available.

9.2 Effect of Containment Design

To obtain further insights into the effectiveness of containment, parametric studies were performed by placing different containments at a plant. The Oconee plant was chosen as the base case system design on which different containments were placed. The containment parameters are presented in Table 26 for each of the containment designs considered. Some of the important assumptions in the analysis are included in Table 26. The same type of analyses could be applied to other plants and other containment designs. The effectiveness of a containment design for a plant depends primarily on the design of the containment (volume, failure pressure, sprays, etc.) and the loadings imposed on the containment which are determined by the characteristics of the important accident sequences at that plant.

Also included on Table 26 are the conditional failure probabilities that are calculated for each containment assuming that containment could be placed on the Oconee plant. The conditional failure probability is defined as the probability of gross containment failure given a core melt. This has been calculated by summing the products of the accident sequence frequency and the containment failure probability for that sequence over all sequences and dividing the sum by the total core melt frequency.

The risks as measured by expected manrem and expected acute fatalities for different containments on Oconee are tabulated in Table 27. The results are presented with and without the V sequence to show the impact of this scenario. The risk worths for the various containments on Oconee are shown in Table 28.

TABLE 26. CONTAINMENT PARAMETERS

Plant	Volume (ft^3)	Design Pressure (psia)	Nominal Failure Pressure(1) (psia)	Conditional Failure Probability(2)
Oconee (Prestressed Concrete)	1.91×10^6	74	133 ± 20	.459
Calvert Cliffs (Prestressed Concrete)	2.0×10^6	65	135 ± 10 135 ± 20	.18 .30
Surry (Reinforced Concrete)	1.8×10^6	60	100 ± 15	.95
Zion (Prestressed Concrete)	2.72×10^6	62	148 ± 4	.01

(1)The nominal failure pressure and failure distribution in each case was taken from a PRA analyses for that plant. For Oconee, Calvert Cliffs, and Surry, the failure distribution was assumed to be Gaussian with the mean equal to the nominal failure pressure and the standard deviation as given. For Oconee, the data was taken from the RSSMAP report which assumed a nominal failure pressure of 2 times the design pressure (in psig) and a standard deviation of 20 psi. The Calvert Cliffs RSSMAP analyses assumed a nominal failure pressure 2.5 times the design pressure (in psig) and a standard deviation of 10 psi. The calculations for the Calvert Cliffs analyses was carried out with two standard deviations to show the effect of this assumption. The data for Surry was identical to the containment analyses in the Reactor Safety Study (100 ± 15) psia. The Zion PRA[17] assumed a different set of assumptions. A greater reliance on the containment to maintain functional integrity is assumed, thus the high failure pressure. The standard deviation is based on statistical variation in materials properties. Because of the relatively large volume and high nominal failure pressure of this design, overpressure failures were negligible risk contributors.

(2)The conditional failure probability is defined as the probability of gross containment failure (RSS Release Categories 1, 2, or 3) given a core melt. All calculations assumed the Oconee system risk profile.

TABLE 27. RISK FOR DIFFERENT CONTAINMENTS ON ONE PLANT[1]

Containment Design Assumptions		Risk: Man Rem	Risk: Acute Fatalities
Oconee	with V	42.	2.2×10^{-3}
	without V	38.	2.0×10^{-3}
Surry	with V	78.	4.2×10^{-3}
	without V	74.	4.0×10^{-3}
Calvert Cliffs			
135 ± 10	with V	20.	1.1×10^{-3}
	without V	16.	9.0×10^{-4}
135 ± 20	with V	31.	1.6×10^{-3}
	without V	27.	1.4×10^{-3}
Zion	with V	5.0	2.4×10^{-4}
	without V	0.6	2.0×10^{-5}
No Containment			
	with V	150.	2.94×10^{-2}
	without V	146.	2.92×10^{-2}
"Perfect Containment"			
	with V	4.4	2.2×10^{-4}
	without V	.04	0.

[1] All values on this table are for the Oconee accident risk profile with the indicated containment design assumptions.

TABLE 28. RISK WORTHS FOR DIFFERENT CONTAINMENTS ON ONE PLANT

Containment Assumed		Risk Reduction Worth				Risk Achievement Worths			
		Interval		Ratio		Interval		Ratio	
		Man Rem	Acute Fatalities	Man Rem	Acute Fatalities	Man Rem	Acute Fatalities	Man Rem	Acute Fatalities
Oconee	with V	38	2.0×10^{-3}	9.5	10	108	2.7×10^{-2}	3.6	13
	without V	38	2.0×10^{-3}	950	∞	108	2.7×10^{-2}	3.8	15
Surry	with V	74	4.0×10^{-3}	18	19	72	2.5×10^{-2}	1.9	7.0
	without V	74	4.0×10^{-3}	1900	∞	72	2.5×10^{-2}	2.0	7.3
Calvert Cliffs									
135 ± 10	with V	16	9.0×10^{-4}	4.5	5.0	130	2.9×10^{-2}	7.5	27
	without V	16	9.0×10^{-4}	400	∞	130	2.9×10^{-2}	9.1	32
135 ± 20	with V	27	1.4×10^{-3}	7.0	7.3	123	2.8×10^{-2}	4.8	18
	without V	27	1.4×10^{-3}	680	∞	123	2.8×10^{-2}	5.4	21
Zion	with V	0.6	2.0×10^{-5}	1.1	1.1	145	2.9×10^{-2}	30	120
	without V	0.6	2.0×10^{-5}	15	∞	145	2.9×10^{-2}	240	1500

The results in Tables 27 and 28 show the importance of the containment design to risk estimates. The risk achievement ratios in Table 28 show how the worth of containment varies with design. Excluding the Zion containment design the containment worths for early fatalities range from about a factor of 10 to about a factor of 30. The worth for the Zion containment design is a factor of 10^2 to 10^3 depending upon whether event V is assumed to be deleted or not. For manrem protection, the ratio worths of containment range from about a factor of 3 to about a factor of 10. The ratio worth of the Zion design is a factor of $\sim$30 to $\sim$100 for manrem reduction, depending upon the event V scenario. The risk achievement worths on an interval scale are not very useful here since the high final risk masks the differences ($R_i^+ - R_0 \approx R_i^+$).

The risk reduction ratios in Table 28 indicate the improvement possible for the containment designs. The risk reduction ratios indicate that the Zion design is near optimal, although hypothetically acute fatalities could be reduced to zero without Sequence V (giving a risk reduction ratio of ∞). Since the acute fatalities for the Zion containment are relatively small, as measured by the risk reduction interval of 2×10^{-5}, further reduction would not have the priority of the other containment designs. For the containment designs other than Zion, the risk reduction ratios for early fatalities range from a factor of 10 upwards. For manrem, the reduction ratios are all about a factor of 10 with V and are all about a factor of 10^3 without V.

Considering the uncertainties in the analyses, the risk achievement and risk reduction worths for all the containment designs except Zion are about the same. The Zion design is worth about a factor of 10 more than the other designs in reducing early fatalities and manrem. Event V reduces the worth of containment by about a factor of 3 for manrem reduction. For early fatalities, the effect of event V is larger as measured by the risk ratio because of the possibility of achieving zero early fatalities if event V is assumed to be deleted.

9.3 Effect of Containment Failure Pressure

While examining the effect of different containments, the risk was found to be sensitive to the assumed failure pressure distribution. There is considerable uncertainty associated with the failure pressure distribution. For the Oconee analyses the nominal failure pressure was taken to be two times the design pressure. The ultimate strength is estimated as approximately three times the design pressure. The failure pressure distribution for Oconee was assumed to be a Gaussian distribution with a mean of 133 psia and a standard deviation of 20 psi. The importance of this assumption to risk estimates can be shown by recalculating the risk using different mean failure pressure assumptions. Two of these assumed values (1 x Design pressure and ultimate strength) were chosen to represent an upper and lower bound on containment effectiveness at this plant. The 2 x Design pressure value represents the based case as assumed in the RSSMAP report. The 2.5 x Design pressure represents greater confidence in the containment to maintain functional integrity under load and may represent more recent analyses.

At the 1 x Design pressure assumption, containment failure is a virtual certainty given the predicted pressure history for the dominant sequences at Oconee. This assumption represents a lower bound of containment effectiveness since the "true" containment failure pressure cannot realistically be this low. The ultimate strength assumption (approximately 3 x Design pressure) represents an upper bound of containment effectiveness. The dominant sequences at Oconee (overpressure by hydrogen burning) have a very low probability of failing containment at this assumed pressure. The dominant risk contributors are steam explosions, leakage, and the V sequence.

At the 2 x Design pressure assumption, the probability of containment failure due to overpressure is significant (.2 to .5) for the dominant sequences. At the 2.5 x Design pressure assumption, the probability of failure due to overpressure is smaller but still significant (.01 to .07).

The same standard deviation about the mean (20 psi) was assumed for all calculations. It should also be mentioned that the failure pressure and the failure mode, and therefore the consequences, may not be independent.(18)

Table 29 shows the risk estimates for a variety of different assumptions on the containment failure pressure. The assumption of mean failure pressure is seen to have over an order of magnitude importance considering the V sequence and two orders of magnitude importance if the V sequence is discounted. The risk as measured by manrem is plotted in Figure 25. The risk worths are presented in Table 30. The risk worths are displayed in Figure 26 for each of the assumed failure pressures with the V sequence discounted. The risk reduction worth and risk achievement worths are seen to be strong functions of the assumed mean failure pressure.

TABLE 29. RISK ESTIMATES AS A FUNCTION OF MEAN FAILURE PRESSURE

Assumption		Risk	
		Man Rem	Acute Fatalities
1 x Design Pressure	with V	89	7.0×10^{-3}
	without V	85	6.8×10^{-3}
2 x Design Pressure	with V	42	$2.2. \times 10^{-3}$
	without V	38	2.0×10^{-3}
2.5 x Design Pressure	with V	11	5.9×10^{-4}
	without V	7	3.9×10^{-4}
Ultimate Strength	with V	5.0	2.4×10^{-4}
	without V	.6	2.0×10^{-5}

9.4 Definition of Containment Reliability Measures

Instead of utilizing risk worth measures, another way of evaluating containment importance is to utilize containment reliability measures. Two measures which can be used to characterize containment reliability are:

P = the probability of any individual dying given a core melt (or source core damage) accident

FIGURE 25. RISK VS MEAN FAILURE PRESSURE AT OCONEE WITH σ = 20 PSI

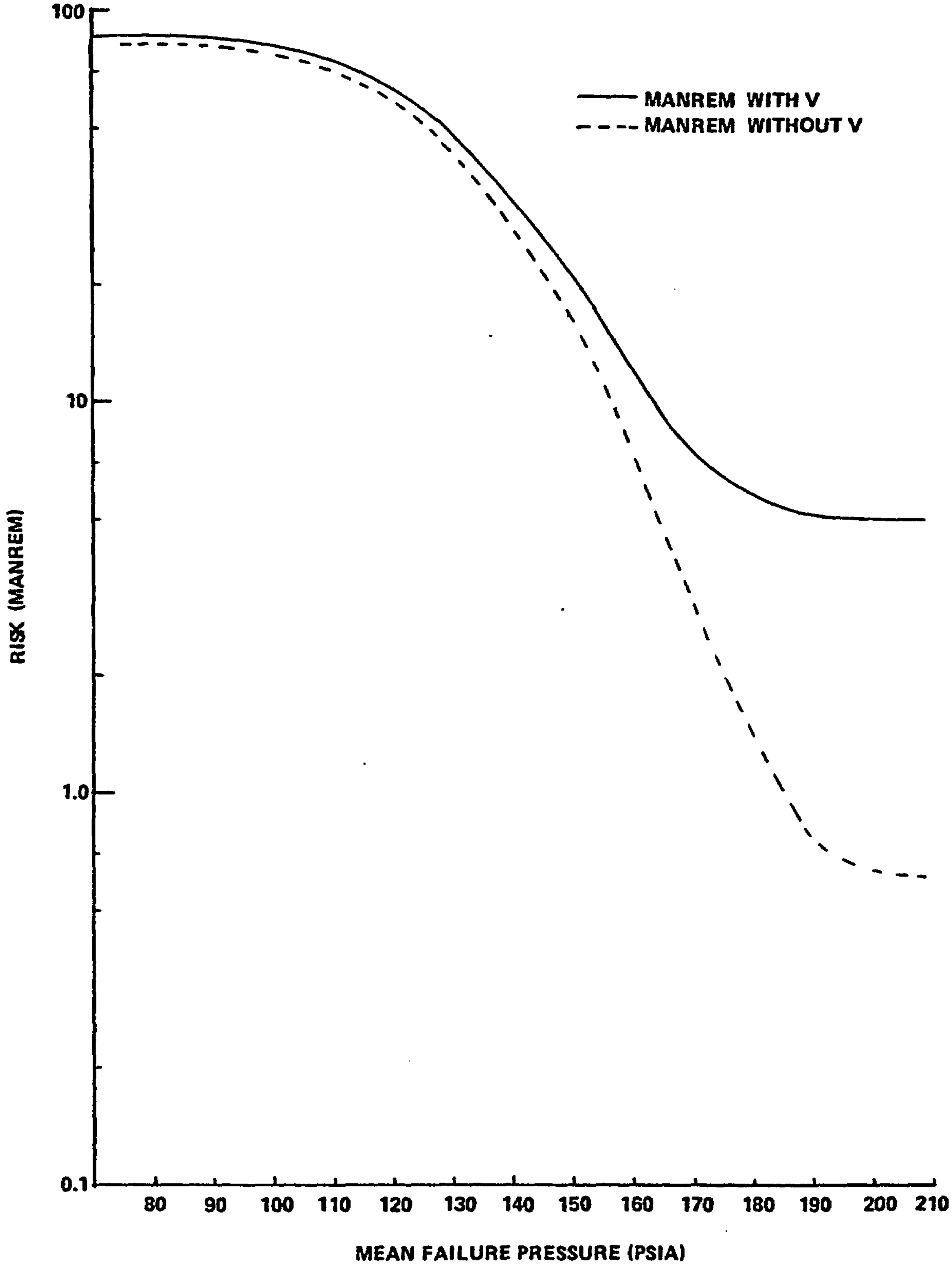


TABLE 30. RISK WORTHS FOR OCONEE AS A FUNCTION OF MEAN FAILURE PRESSURE
(σ = 20 psi)

	Risk Reduction Worth				Risk Achievement Worth			
	Interval		Ratio		Interval		Ratio	
Assumption	Manrem	Acute Fatalities	Manrem	Acute Fatalities	Manrem	Acute Fatalities	Manrem	Acute Fatalities
1 x Design Pressure								
with V	85	6.8×10^{-3}	20	32	61	2.2×10^{-2}	1.7	4.2
without V	85	6.8×10^{-3}	2100	∞	61	2.2×10^{-2}	1.7	4.3
2 x Design Pressure								
with V	38	2.0×10^{-3}	9.5	10	108	2.7×10^{-2}	3.6	13
without V	38	2.0×10^{-3}	950	∞	108	2.7×10^{-2}	3.8	15
2.5 x Design Pressure								
with V	7	3.9×10^{-4}	2.5	2.7	139	2.9×10^{-2}	14	50
without V	7	3.9×10^{-4}	180	∞	139	2.9×10^{-2}	21	75
Ultimate Strength								
with V	.6	2.0×10^{-5}	1.1	1.1	145	2.9×10^{-2}	30	120
without V	.6	2.0×10^{-5}	15	∞	145	2.9×10^{-2}	240	1500

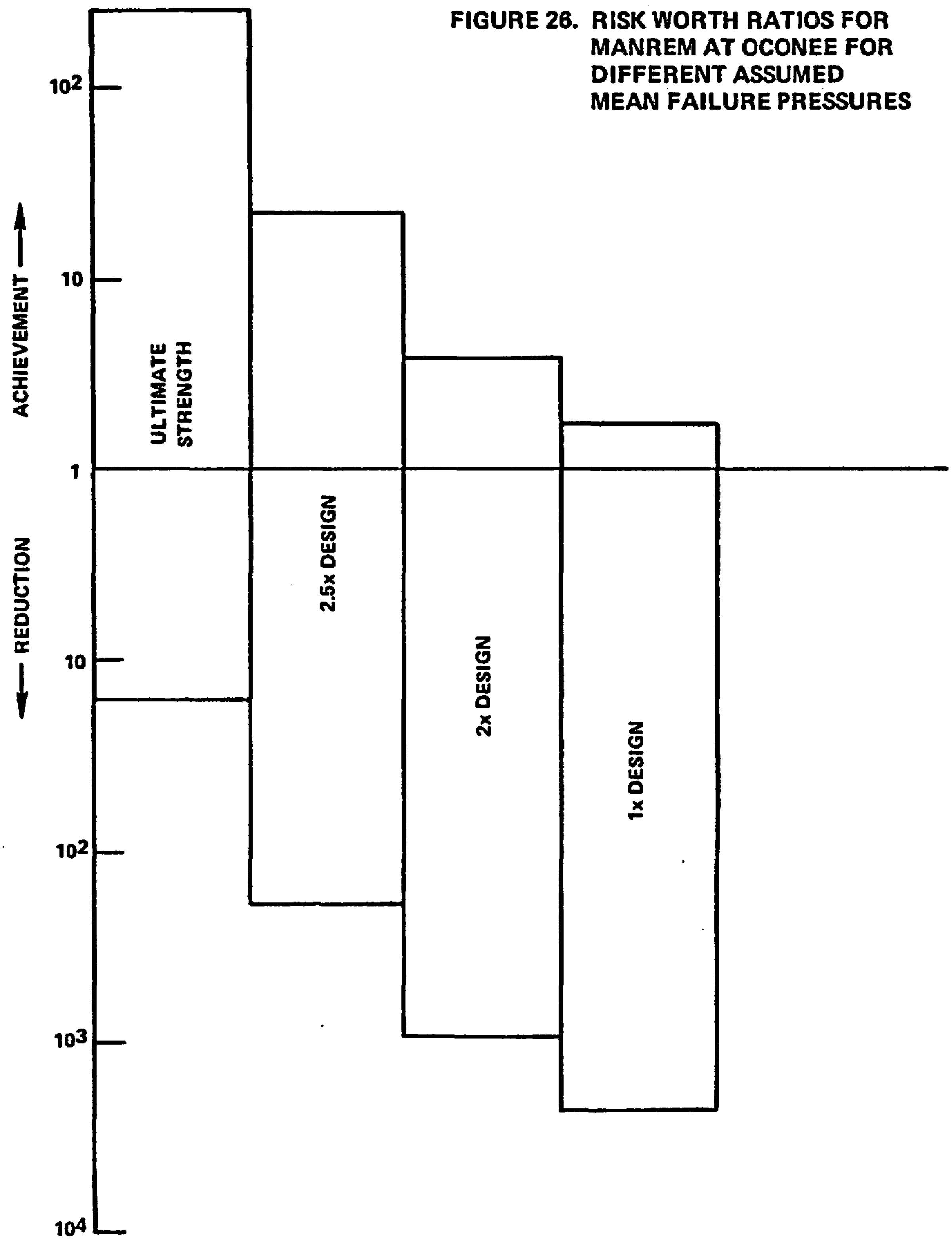


FIGURE 26. RISK WORTH RATIOS FOR MANREM AT OCONEE FOR DIFFERENT ASSUMED MEAN FAILURE PRESSURES

E = the expected number of individuals dying given a core melt or source core damage accident

In the above definitions, the individual or individuals are the public, which are protected by the containment. From the relationship between expectation and probabilities it is known that $E \geq P$ for all cases. Another measure of containment reliability is the probability that more than X individuals are killed where X is some large number. This measure focuses on the containment protecting against large numbers of people dying when a major accident occurred. If P and E are sufficiently small then the probability of killing larger numbers of people will be small.

Instead of focusing on fatalities, the above two measures of containment reliability can also be redefined in terms of radiological releases:

P = the probability that no significant radiological release occurs when a major accident occurs

E = the radiological release which is expected to occur when a major accident occurs

To apply the above definitions, "significant radiological release" would need to be translated to numerical values for explicitly defined isotopes. Explicit criteria would also need to be defined for categorizing an accident sequence as a major accident or one causing source core damage.

For the RSSMAP evaluations, expected acute fatalities are calculated by using factors for each release category. If f_i is the release category frequency and a_i is the acute fatalities factor for that category, then the expected acute fatalities A is simply

$$A = \Sigma f_i a_i$$

where the sum is over the release categories.

If acute fatalities are focused upon then the containment reliability measure E can be simply expressed in terms of A:

$$E = \frac{A}{f_i}$$

$$= \frac{\Sigma f_i a_i}{\Sigma f_i}$$

Thus E is the weighted average of the release category frequencies where each release category is weighted by its acute fatality importance a_i.

In a similar way, the expected manrem which is calculated for the RSSMAP conclusions can be related to the containment reliability measure in terms of expected release. The expected manrem M is calculated by

$$M = \Sigma f_i m_i$$

where m_i is the manrem factor for a release category i. If release is expressed as manrem then the containment reliability measure in terms of expected release E is simply related to M by

$$E = \frac{M}{\Sigma f_i}$$

$$= \frac{\Sigma f_i m_i}{\Sigma f_i}$$

Thus E is a weighted average of the release category frequencies where the weight is now M_i which is the importance of the category in terms of manrem release.

TABULATION OF CONTAINMENT RELIABILITY MEASURES FROM RSSMAP

Table 31 lists the acute reliability measure E for those cases evaluated in the RSSMAP analyses. Table 32 lists the manrem reliability measure for the RSSMAP cases. These values in Tables 31 and 32 are relatively high since no evacuation was assumed for the consequence evaluations.

This was purposely done to separate the effect of containment from the effect of evacuation. The reliability measures tend to focus on the consequences. As observed from the table, within about a factor of 2, the containment reliability measures for expected fatalities and expected manrem are all about the same, about 50 expected acute fatalities and about 1×10^6 expected manrem per core melt. These relatively high values indicate that the consequences of core melts are not necessarily benign and that containment design improvements and other improvements in mitigative measures could significantly reduce these values.* The previous risk worth evaluations on containment gave risk reduction ratios of at least 10 which, if initiated, would result in expected acute fatalities being less than ~ 5 and expected manrem being less than $\sim 10^5$ with the no evacuation assumption.

TABLE 31. CONTAINMENT RELIABILITY MEASURES FOR ACUTE FATALITIES FOR THE RSSMAP PLANTS ASSUMING NO EVACUATION

Plant	$A = \Sigma f_i a_i$	Σf_i	E
Sequoyah	3.2×10^{-3}	5.6×10^{-5}	57
Oconee	2.6×10^{-3}	8.2×10^{-5}	32
Calvert Cliffs	1.2×10^{-1}	2.0×10^{-3}	60
Grand Gulf	2.0×10^{-3}	3.6×10^{-5}	56

*Because of RSSMAP's conservative modeling, the values in Tables 31 and 32 can be significantly higher than those calculated using more realistic analyses. These conclusions are thus dependent on the RSSMAP results and would need to be validated before any implementation is pursued. This conclusion is also dependent on the source term assumptions which are currently being reevaluated.

TABLE 32. CONTAINMENT RELIABILITY MEASURES FOR EXPECTED MANREM FOR THE RSSMAP PLANTS ASSUMING NO EVACUATION

Plant	$M = \Sigma f_i m_i$	Σf_i	E
Sequoyah	67	5.6×10^{-5}	1.2×10^{6}
Oconee	48	8.2×10^{-5}	5.9×10^{5}
Calvert Cliffs	2200	2.0×10^{-3}	1.1×10^{6}
Grand Gulf	83	3.6×10^{-5}	2.3×10^{6}

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APPENDIX A

EXAMPLE RISK WORTHS FOR OTHER RISK MEASURES

TABLE A-1. RISK REDUCTION WORTHS FOR OCONEE SAFETY SYSTEMS

System	Risk Reduction Worth: Interval: Core Melt Frequency	Interval: Man Rem	Interval: Acute Fatalities	Ratio: Core Melt Frequency	Ratio: Manrem	Ratio: Acute Fatalities
Auxiliary Feedwater	3.0×10^{-6}	1.9	1.0×10^{-4}	1.0	1.0	1.0
Pressurizer Relief Valve (Stuck Open)	1.8×10^{-5}	10	5.6×10^{-4}	1.3	1.3	1.3
High Pressure Injection	1.4×10^{-5}	8.5	4.7×10^{-4}	1.2	1.3	1.3
Low Pressure Injection	8.8×10^{-6}	2.0	1.2×10^{-4}	1.1	1.1	1.1
Emergency Core Cooling Recirculation	3.3×10^{-5}	19	1.0×10^{-3}	1.9	1.8	1.8
Service Water	1.5×10^{-5}	12	6.4×10^{-4}	1.3	1.3	1.3
Electric Power (On-Site)	2.2×10^{-6}	1.8	9.6×10^{-5}	1.0	1.0	1.0
Reactor Protection System	7.8×10^{-6}	4.8	2.6×10^{-4}	1.1	1.1	1.1
High Head Service Water	2.2×10^{-6}	1.4	7.4×10^{-5}	1.0	1.0	1.0

TABLE A-2. RISK ACHIEVEMENT WORTHS FOR OCONEE SAFETY SYSTEMS

System	Risk AchievementWorth					
	Interval			Ratio		
	Core Melt Frequency	Man Rem	Acute Fatalities	Core Melt Frequency	Manrem	Acute Fatalities
Auxiliary Feedwater	7.5×10^{-3}	4700	.25	110	110	110
Pressurizer Relief Valve (Stuck Open)	3.3×10^{-4}	200	.011	5.6	5.7	5.7
High Pressure Injection	3.4×10^{-3}	2100	.12	48	50	52
Low Pressure Injection	5.0×10^{-4}	120	.0067	7.8	3.9	4.1
Emergency Core Cooling Recirculation	3.4×10^{-3}	1900	.11	48	35	37
Service Water	.54	4.3×10^{-5}	24	7500	7900	8100
Electric Power (On-Site)	4.4×10^{-3}	3500	.19	62	65	67
Reactor Protection System	.30	1.9×10^{5}	10	4100	4400	4500
High Head Service Water	2.0×10^{-5}	12	6.7×10^{-4}	1.3	1.3	1.3

TABLE A-3. RISK REDUCTION WORTHS FOR HUMAN ACTIONS AT OCONEE

Individual Human Actions	Risk Reduction Worth: Interval: Core Melt Frequency	Interval: Man Rem	Interval: Acute Fatalities	Ratio: Core Melt Frequency	Ratio: Manrem	Ratio: Acute Fatalities
Operator Fails to Start the High Pressure Injection System	1.3×10^{-5}	8.2	4.4×10^{-4}	1.2	1.2	1.2
Failure of Operator to Align Suction of HPRS to Discharge of LPRS	8.4×10^{-6}	5.2	2.8×10^{-4}	1.1	1.1	1.1
Operator Leaves LP Pump Train Test Valves in Wrong Position	9.9×10^{-6}	5.6	3.1×10^{-4}	1.2	1.2	1.2
Operator Fails to Open Sump Valves at the Start of Recirculation	9.6×10^{-6}	4.8	2.8×10^{-4}	1.2	1.1	1.2
Common Mode Miscalibration of Instruments Which Actuate HPIS	9.0×10^{-8}	0.056	3.0×10^{-6}	1.0	1.0	1.0
Operator Fails to Manually Start High Head Auxiliary Service Water	2.2×10^{-6}	1.3	7.3×10^{-5}	1.0	1.0	1.0

TABLE A-4. RISK ACHIEVEMENT WORTHS FOR HUMAN ACTIONS AT OCONEE

	Risk Achievement Worth					
	Interval			Ratio		
Individual Human Actions	Core Melt Frequency	Man Rem	Acute Fatalities	Core Melt Frequency	Manrem	Acute Fatalities
Operator Fails to Start the High Pressure Injection System	4.3×10^{-4}	260	0.014	6.9	7.2	7.4
Failure of Operator to Align Suction of HPRS to Discharge of LPRS	2.8×10^{-3}	1700	0.094	40	42	43
Operator Leaves LP Pump Train Test Valves in Wrong Position	3.3×10^{-3}	1900	0.10	47	45	46
Operator Fails to Open Sump Valves at the Start of Recirculation	3.2×10^{-3}	1600	0.076	45	38	35
Common Mode Miscalibration of Instruments Which Actuate HPIS	2.8×10^{-3}	1700	0.094	40	42	43
Operator Fails to Manually Start High Head Auxiliary Service Water	1.9×10^{-5}	12	6.5×10^{-4}	1.3	1.3	1.3

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16. ABSTRACT *(200 words or less)*

The objectives of this work are to evaluate the importance of the containment and the different safety functions as assessed in probabilistic risk analyses. To accomplish this objective, risk importance measures are defined to evaluate a feature's importance in further reducing the risk and its importance in maintaining the present risk level. One defined importance measure, called the feature's risk reduction worth, is useful for prioritizing feature improvements which can most reduce the risk. The other defined importance, called the feature's risk achievement worth, is useful for prioritizing features which are most important in reliability assurance and maintenance activities.

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