2

Evaluation of Severe Accident Risks: Methodology for the Containment, Source Term, Consequence, and Risk Integration Analyses

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Sandia National Laboratories
Operated by
Sandia Corporation

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W. B. Murfin[2], F. T. Harper, S. C. Hora[3]

Sandia National Laboratories
Albuquerque, NM 87185–5800

[1]Arizona State University, Tempe, AZ 85287
[2]Technadyne Engineering Consultants, Inc., Albuquerque, NM, 87112
[3]University of Hawaii, Hilo, HI 96720–4091

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ABSTRACT

NUREG-1150 examines the risk to the public from five nuclear power plants. The NUREG-1150 plant studies are Level III probabilistic risk assessments (PRAs) and, as such, they consist of four analysis components: accident frequency analysis, accident progression analysis, source term analysis, and consequence analysis. This volume summarizes the methods utilized in performing the last three components and the assembly of these analyses into an overall risk assessment. The NUREG-1150 analysis approach is based on the following ideas: (1) general and relatively fast-running models for the individual analysis components, (2) well-defined interfaces between the individual analysis components, (3) use of Monte Carlo techniques together with an efficient sampling procedure to propagate uncertainties, (4) use of expert panels to develop distributions for important phenomenological issues, and (5) automation of the overall analysis. Many features of the new analysis procedures were adopted to facilitate a comprehensive treatment of uncertainty in the complete risk analysis. Uncertainties in the accident frequency, accident progression and source term analyses were included in the overall uncertainty assessment. The uncertainties in the consequence analysis were not included in this assessment. A large effort was devoted to the development of procedures for obtaining expert opinion and the execution of these procedures to quantify parameters and phenomena for which there is large uncertainty and divergent opinions in the reactor safety community.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF TABLES

FOREWORD

This is one of numerous documents that support the preparation of the final NUREG-1150 document by the Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research. Figure 1 illustrates the documentation of the accident progression, source term, consequence, and risk analyses. The direct supporting documents for the first draft of NUREG-1150 and for the revised draft of NUREG-1150 are given in Table 1. They were produced by the three interfacing programs that performed the work -- the Accident Sequence Evaluation Program (ASEP) at Sandia National Laboratories, the Severe Accident Risk Reduction Program (SARRP), and the PRA Phenomenology and Risk Uncertainty Evaluation Program (PRUEP). The Zion volumes were written by Brookhaven National Laboratory and Idaho National Engineering Laboratory.

The Accident Frequency Analysis, and its constituent analyses, such as the Systems Analysis and the Initiating Event Analysis, are reported in NUREG/CR-4550. Originally, NUREG/CR-4550 was published without the designation "Draft for Comment." Thus, the current revision of NUREG/CR-4550 is designated Revision 1. The label Revision 1 is used consistently on all volumes, including Volume 2 which was not part of the original documentation. NUREG/CR-4551 was originally published as a "Draft for Comment." While the current version could have been issued without a revision indication, all volumes of NUREG/CR-4551 have been designated Revision 1 for consistency with NUREG/CR-4550.

The material contained in NUREG/CR-4700 in the original documentation is now contained in NUREG/CR-4551; NUREG/CR-4700 is not being revised. The contents of the volumes in both NUREG/CR-4550 and NUREG/CR-4551 have been altered. In both documents now, Volume 1 describes the methods used in the analyses, Volume 2 presents the elicitation of expert judgment, Volume 3 concerns the analyses for Surry, Volume 4 concerns the analyses for Peach Bottom, and so on as shown in Table 1.

In addition to NUREG/CR-4550 and NUREG/CR-4551, there are several other reports published in association with NUREG-1150 that explain the methods used, document the computer codes that implement these methods, or present the results of calculations performed to obtain information specifically for this project. These reports include:

> NUREG/CR-5032, SAND87-2428, Modeling Time to Recovery and Initiating Event Frequency for Loss of Off-site Power Incidents at Nuclear Power Plants, R. L. Iman and S. C. Hora, Sandia National Laboratories, Albuquerque, NM, January 1988.

> NUREG/CR-4840, SAND88-3102, Procedures for External Core Damage Frequency Analysis for NUREG-1150, M. P. Bohn and J. A. Lambright, Sandia National Laboratories, Albuquerque, NM, December 1988.

NUREG/CR-5174, SAND88-1607, J. M. Griesmeyer and L. N. Smith, A Reference Manual for the Event Progression and Analysis Code (EVNTRE), Sandia National Laboratories, Albuquerque, NM, September 1989.

NUREG/CR-5380, SAND88-2988, S. J. Higgins, A User's Manual for the Post Processing Program PSTEVNT, Sandia National Laboratories, Albuquerque, NM, November 1989.

NUREG/CR-4624, BMI-2139, R. S. Denning et al., Radionuclide Release Calculations for Selected Severe Accident Scenarios, Volumes I-V, Battelle Columbus Division, Columbus, OH, 1986.

NUREG/CR-5062, BMI-2160, M. T. Leonard et al., Supplemental Radionuclide Release Calculations for Selected Severe Accident Scenarios, Battelle Columbus Division, Columbus, OH, 1988.

NUREG/CR-5331, SAND89-0072, S. E. Dingman et al., MELCOR Analyses for Accident Progression Issues, Sandia National Laboratories, Albuquerque, NM, November 1990.

NUREG/CR-5253, SAND88-2940, R. L. Iman, J. C. Helton, and J. D. Johnson, PARTITION: A Program for Defining the Source Term/Consequence Analysis Interfaces in the NUREG-1150 Probabilistic Risk Assessments User's Guide, Sandia National Laboratories, Albuquerque, NM, May 1990.

SUPPORT DOCUMENTS TO NUREG-1150

NUREG-1150
(NRC Staff)

NUREG/CR-4550

CORE DAMAGE FREQUENCY

METHODOLOGY — METHODS Vol. 1
APPENDICES

EVALUATION OF SEVERE ACCIDENT RISKS NUREG/CR-4551

IN-VESSEL ISSUES — MAJOR INPUT PARAMETERS Vol. 2
CONTAINMENT LOADS & MCCI ISSUES
STRUCTURAL RESPONSE ISSUES
SOURCE TERM ISSUES
SUPPORTING CALCULATIONS
OTHER ISSUES
MACCS INPUT

ANALYSIS & RESULTS — SURRY Vol. 3
APPENDICES

ANALYSIS & RESULTS — PEACH BOTTOM Vol. 4
APPENDICES

ANALYSIS & RESULTS — SEQUOYAH Vol. 5
APPENDICES

ANALYSIS & RESULTS — GRAND GULF Vol. 6
APPENDICES

ANALYSIS & RESULTS — ZION Vol. 7
APPENDICES

Figure 1.   Back-End Documentation for NUREG-1150.

Table 1. NUREG-1150 Analysis Documentation

Original Documentation

NUREG/CR-4550	NUREG/CR-4551	NUREG/CR-4700
Analysis of Core Damage Frequency From Internal Events	Evaluation of Severe Accident Risks and the Potential for Risk Reduction	Containment Event Analysis for Potential Severe Accidents

Vol.			Vol.			Vol.		
	1	Methodology		1	Surry Unit 1		1	Surry Unit 1
	2	Summary (Not Published)		2	Sequoyah Unit 1		2	Sequoyah Unit 1
	3	Surry Unit 1		3	Peach Bottom Unit 2		3	Peach Bottom Unit 2
	4	Peach Bottom Unit 2		4	Grand Gulf Unit 1		4	Grand Gulf Unit 1
	5	Sequoyah Unit 1						
	6	Grand Gulf Unit 1						
	7	Zion Unit 1						

Revised Documentation

NUREG/CR-4550, Rev. 1, Analysis of Core Damage Frequency				NUREG/CR-4551, Rev. 1, Eval. of Severe Accident Risks			
Vol. 1		Methodology		Vol. 1		Methodology	
2	Part 1	Expert Judgment Elicit. Expert Panel		2	Part 1	In-Vessel Issues	
	Part 2	Expert Judgment Elicit. Project Staff			Part 2	Containment Loads and MCCI Issues	
					Part 3	Structural Issues	
					Part 4	Source Term Issues	
					Part 5	Supporting Calculations	
					Part 6	Other Issues	
					Part 7	MACCS Input	
3	Part 1	Surry Unit 1 Internal Events		3	Part 1	Surry Analysis and Results	
	Part 2	Surry Unit 1 Internal Events App.			Part 2	Surry Appendices	
	Part 3	Surry External Events					
4	Part 1	Peach Bottom Unit 2 Internal Events		4	Part 1	Peach Bottom Analysis and Results	
	Part 2	Peach Bottom Unit 2 Int. Events App.			Part 2	Peach Bottom Appendices	
	Part 3	Peach Bottom Unit 2 External Events					
5	Part 1	Sequoyah Unit 1 Internal Events		5	Part 1	Sequoyah Analysis and Results	
	Part 2	Sequoyah Unit 1 Internal Events App.			Part 2	Sequoyah Appendices	
6	Part 1	Grand Gulf Unit 1 Internal Events		6	Part 1	Grand Gulf Analysis and Results	
	Part 2	Grand Gulf Unit 1 Internal Events App.			Part 2	Grand Gulf Appendices	
7		Zion Unit 1 Internal Events		7	Part 1	Zion Analysis and Results	
					Part 2	Appendices	

ACKNOWLEDGMENTS

ACRONYMS AND INITIALISMS

AFW   auxiliary feedwater
AFWS   auxiliary feedwater system
APB   accident progression bin
APET   accident progression event tree
AS   accident sequence
ASEP   accident sequence evaluation program
ATWS   anticipated transient without scram

BCL   Battelle Columbus Laboratory
BMT   basemat melt-through
BNL   Brookhaven National Laboratory
BWR   boiling water reactor

CCI   core-concrete interaction
CCDF   complementary cumulative distribution function
CD   core damage
CDF   cumulative distribution function
CF   containment failure
CHR   containment heat removal
CCW   component cooling water

ECCS   emergency core cooling system(s)
EPA   Environmental Protection Agency
EPRI   Electric Power Research Institute
EPZ   emergency planning zone

HPI   high pressure injection
HPIS   high pressure injection system
HPME   high pressure melt ejection
HX   heat exchangers

IE   initiating event
INEL   Idaho National Engineering Laboratory

LHS   Latin Hypercube Sampling
LLNL   Lawrence Livermore National Laboratory
LOCA   loss-of-coolant accident
LPIS   low pressure injection system
LWR   light water reactor

MCDF   mean core damage frequency
MCS   minimal cut set
MFWS   main feedwater system

NRC   Nuclear Regulatory Commission

PDS   plant damage state
PORV   power-operated relief valve
PRA   probabilistic risk analysis

PRUEP	Phenomenological and Risk Uncertainty Evaluation Program
PWR	pressurized water reactor
QC	quality control
RCP	reactor coolant pump
RCS	reactor coolant system
RWST	refueling water storage tank
SAIC	Science Applications International Corporation
SAROS	Safety and Reliability Optimization Services
SAARP	Severe Accident Risk Reduction Program
SBO	station blackout
SG	steam generator
SGTR	steam generator tube rupture
SNL	Sandia National Laboratories
SRV	safety relief valve
ST	source term
STG	source term group
STSG	source term subgroup
SW	service water
VB	vessel breach

1.0 INTRODUCTION

1.1 Background

The U.S. Nuclear Regulatory Commission (NRC) has completed a major study to provide a current characterization of the risk from severe accidents at light water reactors (LWRs). This characterization was derived from the analysis of five nuclear power plants. The summary report of that work, Severe Accident Risks: An Assessment of Five U.S. Nuclear Power Plants (hereafter referred to as NUREG-1150[1]), is based on extensive investigations by Sandia National Laboratories (SNL) and other NRC contractors. Several series of reports document in detail these investigations and their results.

The investigations included Level III probabilistic risk assessments* for all five plants. These risk assessments can be characterized as consisting of four analysis components, an analysis integration component and an uncertainty analysis component:

- Accident frequency analysis, which determines the likelihood and nature of accidents that result in the onset of core damage;

- Accident progression analysis, which investigates the core damage process both in and outside the reactor vessel and the resultant impact on containment;

- Source term analysis, which estimates the radionuclide releases associated with specific accident conditions;

- Consequence analysis, which calculates the offsite consequences in terms of health effects and financial loss;

- Risk integration, which assembles the results of the preceding analysis components into an overall expression of risk; and

- Uncertainty analysis, which estimates the uncertainty in the risk results due to uncertainty in the characterization of important physical and chemical phenomena.

Five plants were analyzed: Surry Unit 1, Peach Bottom Unit 2, Sequoyah Unit 1, Grand Gulf Unit 1, and Zion Unit 1. The first four plants were analyzed by the staff at SNL while the Zion analyses were completed by Brookhaven National Laboratory (BNL) and Idaho National Engineering Laboratory (INEL). Figure 1 in

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*The level of a PRA is used to identify the analysis components that are included in the PRA. A Level I PRA consists of the accident frequency analysis. A Level II PRA consists of the accident frequency, accident progression and source term analyses. A Level III PRA consists of the accident frequency, accident progression, source term, and consequence analyses. In a Level III PRA the analysis components are combined and an expression for risk developed. The term Level II/III analysis, however, only refers to the accident progression, source term, and consequence analyses.

the foreword shows the principal documents describing the NUREG-1150 study and supporting analyses and their relationships to each other. The methods used to conduct the systems analyses for the four plants are described in the first volume of the NUREG/CR-4550 series. Other volumes describe the results of the systems analyses for all five plants. Two of the plant studies, for Surry and Peach Bottom, include external events as accident initiators (earthquakes, fires, floods, etc.) while the other three studies were limited to internal events as initiators.

This report is the first of seven volumes of the NUREG/CR-4551 series that describe the last five analysis components listed above, covering the progression of the accident once damage is initiated through to an integrated estimate of overall risk and uncertainty in risk for all five plants. This particular volume describes the methods used in these analyses, which were uniform for all five plants studied, while the remaining volumes focus on inputs and results for the particular plants and on inputs to the uncertainty analysis. This volume contains the information needed to understand why particular methods were selected or developed, how they were employed, and the display of results. A summary description of these methods, which provides less detail then this volume, is available in Reference 2.

The uncertainty analyses were important components of these studies. Detailed uncertainty analyses, representing uncertainties in phenomenology, were included in all parts of the analysis except for the offsite consequence evaluation. However, stochastic uncertainties in weather data have been included in the consequence analyses.

While all of the basic inputs and outputs are described in this series of reports, it should be recognized that there were many other documents and calculations specifically in support of this program. These other sources are referenced where appropriate, or summaries are provided as appendices.

1.2   Objectives of the NUREG-1150 Study

The overall objectives of the NUREG-1150 study are discussed in detail in Reference 1. The main objectives are:

- To provide a current assessment of the severe accident risks of five nuclear power plants of different design which:

    - Provides a snapshot of the risks reflecting plant design and operational characteristics, related failure data, and severe accident phenomenological information available as of March 1988;

    - Updates the estimates of the NRC's 1975 risk assessment, the Reactor Safety Study;[3]

- Includes quantitative estimates of risk uncertainty, in response to the principal criticism of the Reactor Safety Study;[4] and

- Identifies plant-specific risk vulnerabilities for the five plants studied, supporting the development of the NRC's individual plant examination (IPE) process.

- To summarize the perspectives gained in performing these risk analyses, with respect to:

  - Issues significant to severe accident frequencies, consequences, and risks;

  - Risk-significant uncertainties that may merit further research;

  - Comparisons with NRC's safety goals; and

  - The potential benefits of a severe accident management program in reducing accident frequencies; and

- Provide a set of PRA models and results that can support the ongoing prioritization of potential safety issues and related research.

- To make explicit use of the data base of severe accident experimental and calculational information generated by NRC's contractors and the nuclear industry.

To obtain risk results, it is necessary to assemble the accident frequency, accident progression, source term, and consequence analyses into an overall, integrated risk assessment. The objectives of the NUREG-1150 analyses placed a number of requirements on the computational procedures used to perform the analyses associated with the individual components and to assemble these analyses into an overall risk assessment, including

- performance of consistent risk calculations through the four analysis components,

- calculation and display of intermediate results,

- traceability throughout the computations,

- results at different levels of resolution,

- quantitative uncertainty and sensitivity analysis,

- incorporation of information of many types and from many sources,

- quality control,

- computational practicality,

- representation of the many different paths along which an accident might evolve.

In turn, the preceding requirements lead to an analysis approach based on the following ideas:

- general and relatively fast-running models for the individual analysis components,

- well-defined interfaces between the individual analysis components,

- use of Monte Carlo techniques in conjunction with an efficient sampling procedure to propagate uncertainties,

- use of expert panels to develop distributions for important phenomenological issues,

- automation of the overall analysis.

The primary purpose of this document is to describe how these ideas were implemented in the NUREG-1150 analyses.

1.3 Quality Control and Reviews

The NUREG-1150 methodology represents the integration of an enormous amount of information. Also, a massive amount of information is transferred across the interfaces of the different analysis modules (system analysis, containment analysis, radionuclide transport, and consequence analysis). For these reasons, it is necessary to set up an effective quality control (QC) system. The five functions of the QC plan developed for the second draft of the NUREG-1150 analysis are briefly described below:*

1) Purpose of QC Plan -- This section of the QC plan briefly describe the project, its purpose, and organization. This represents the scope of the activity to be covered by the plan.

2) Individual Responsibility and Authority -- All review processes, including requirements, design, documentation and software are described in detail. Methods of revision, whether of documentation, software, the QC plan itself, or even project requirements are presented such that anyone associated with the project knows how to initiate a change. In conjunction

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* Memo from Sarah Higgins (SNL) to Elaine Gorham-Bergeron on Quality Assurance, sent Aug. 4, 1988.

with these processes, it is imperative to describe who has responsibility and the line of authority, such that one person's unavailability does not unduly hamper another's progress.

3) Accountability -- This section deals with record accountability, as well as that of individuals, and answers such questions such as : Who keeps what records? Where? Who reports what activity and to whom do they report it? How are records kept of decisions made over the telephone, during informal conversations and during formal meetings?

4) Documentation and Record Keeping -- This portion of the QC plan describes where documents will be maintained (with old versions of documentation removed as new are added, or with outdated versions clearly marked) such that anyone needing project information can readily avail themselves of it.

5) Software Control -- The specific software review process and rules for documenting as well as executing changes are separately addressed. Responsibility for all the codes used by the project, their maintenance, backup-devices to prevent loss in case of disk failure, manuals, hard copy listings, and examples of program usage are all areas addressed by the QC plan.

The second draft of NUREG-1150 had a formal internal quality control team consisting of 12 individuals from SNL, BNL, BCL, and SAROS. Because NUREG-1150 involved methodology and code development, the quality control effort was larger than would be expected of effort using established methods. During the NUREG-1150 effort, it was necessary to verify and validate the codes that were developed for the effort. Most of the code verification and validation was performed internally by SNL staff, however, because BNL was also using the codes additional checking was performed. Also, due to the many review comments received on the XSOR methodology (see Section 7.5), BCL reviewed the XSOR codes.[5]

Peer Review

Because the NUREG-1150 effort was a highly visible program, there were several peer review groups asked to perform reviews on the project. This review goes beyond what would be expected if applying previously developed methods and would not be considered part of the normal QC process. It is discussed here for completeness. The methodology for calculating the uncertainty in risk was one of the major issues of concern for the many peer review groups that reviewed NUREG-1150. The formal peer reviews performed on NUREG-1150 are listed below:

Draft NUREG-1150

    Review by Kouts Committee
    Review by Kastenberg Committee
    Review by American Nuclear Society
    Review by Advisory Committee on Reactor Safeguards

> Review by Special Committee to Review the Severe Accident Risks Report (an international committee formed under the provisions of the Federal Advisory Committee Act)
>
> Review by American Nuclear Society Special Committee on NUREG-1150
>
> Review by Advisory Committee on Reactor Safeguards

The membership of the above mentioned peer review committees are provided and the comments of the committees are summarized in Volume 3 of NUREG-1150 and are not repeated here.

1.4   Organization of this Volume

This volume describes the methods used for the accident progression, source term, consequence, risk integration and uncertainty analyses. Chapter 2 discusses the way in which risk is defined for the NUREG-1150 studies. Chapter 3 describes the main ideas underlying the computational framework used in NUREG-1150. Chapter 4 provides an overview of the analysis process and introduces the mathematical notation used throughout the volume. Chapters 5 through 9 describe the individual analysis steps in greater detail and their assembly to produce a complete risk study. The network codes and file processors used to calculate risk are outlined in Appendix A. A listing of the risk integration code, RISQUE, is provided in Appendix B. Appendix C contains additional information on the development and quantification of the accident progression model and is intended to supplement the information in Chapter 6.

1.5 References

1. U.S. Nuclear Regulatory Commission, _Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants_, NUREG-1150, Final Report, December 1990.

2. Breeding, R. J., et al., Summary Description of the Methods Used in the Probabilistic Risk Assessments for NUREG-1150, Nucl. Eng. Design _135_, 1-27, 1992.

3. U. S. Nuclear Regulatory Commission, _Reactor Safety Study--An Assessment of Accident Risks in U. S. Commercial Nuclear Power Plants_, WASH-1400 (NUREG-75/014), Washington, DC, 1975.

4. Lewis, H. W., et al., _Risk Assessment Review Group Report to the U. S. Nuclear Regulatory Commission_, NUREG/CR-0400, September 1978.

5. Cybulkis, P., _Assessment of the XSOR Codes_, NUREG/CR-5346, BMI-2171, Battelle Columbus Division, Columbus, OH, November 1989.

2.0 REPRESENTATION OF RISK IN NUREG-1150

2.1 Representation of Risk

The NUREG-1150 analyses are based on the representation of risk[1] by a collection of triples of the form

$$R = \{ (s_i, f_i, o_i), i = 1, \ldots nS \} \qquad \text{(Eq. 2.1)}$$

where

s_i =   a scenario (i.e., accident) that leads to an outcome (i.e., result) of interest,

f_i =   frequency (units: yr^{-1}) for scenario i,

o_i =   outcome (units: as appropriate for the outcome under consideration) associated with scenario i,

and

nS =   number of scenarios under consideration.

The essence of a probabilistic risk assessment is the determination of the triples that constitute the set R. Specifically, detailed procedures are used to determine the scenarios and compute their frequencies. Further, additional calculations are often required to determine the outcomes associated with scenarios.

It is difficult to inspect a set R of the form shown in (Eq. 2.1) and draw conclusions with respect to risk if nS is a large number. Therefore, the results contained in R are typically summarized in various ways. When the outcomes are numeric and are ordered so that $o_i \leq o_{i+1}$, a plot of the points

$$(o_i, \sum_{j=i+1}^{nS} f_j), i = 1, \ldots, nS, \qquad \text{(Eq. 2.2)}$$

provides a useful summary. An example of such an exceedance frequency curve is shown in Figure 2-1. The outcome o is plotted on the x-axis (abscissa) and the frequency with which accidents occur that have outcomes greater than o is plotted on the y-axis (ordinate). Exceedance frequency curves provide an answer to questions of the form "How likely is it that an accident will be this bad or worse?" An exceedance frequency curve is analogous to a complementary cumulative distribution function (CCDF) except that the ordinate displays frequency rather than probability.

When the results contained in R are numeric, they can also be summarized as an annual risk value r by the summation

2.1

$$r = \sum_{i=1}^{nS} f_i o_i \qquad\qquad \text{(Eq. 2.3)}$$

Although an annual risk value can be a useful summary measure, information is lost in its generation since it is the result of reducing an exceedance frequency curve to a single number. The results contained in R can also be used to determine the risk due to specific sets of scenarios or the fractional contributions of such sets to annual risk.

In practice, the triples (s_i, f_i, o_i) are more complex than shown in (Eq. 2.1). A scenario is usually not a single accident. Rather, a scenario is a set of similar accidents that are grouped together to help keep the calculations that must be performed for a probabilistic risk assessment on a reasonable scale. In this case, f_i is the sum of the frequencies for a set of similar accidents rather than the frequency for a single specific accident. Most scenarios have many different outcomes associated with them. Thus, a typical scenario actually has a vector of outcomes associated with it. With these expansions, the representation for risk in (Eq. 2.1) becomes

$$R = \{ (S_i, f_i, o_i), i = 1, \ldots, nS \} , \qquad\qquad \text{(Eq. 2.4)}$$

where

> S_i = a scenario (i.e., a set of similar accidents),
> o_i = vector of outcomes associated with scenario i,

and f_i and nS are the same as before.

The scenarios S_i and the corresponding outcomes o_i are often defined in several different ways within a single probabilistic risk assessment. For example, the scenarios might be accidents leading to core damage, and the outcomes could be the status of the different engineered safety systems required to mitigate the effects of core damage. As another example, the scenarios might be sets of accidents leading to radionuclide releases to the environment, and the outcomes could be the source terms that characterize these releases. Finally, the scenarios might be sets of accidents that lead to similar health and economic impacts, and the outcomes could be consequence measures such as fatalities and costs that result from these impacts.

Probabilistic risk assessments must be carefully planned so that it is possible to efficiently generate representations for risk of the form shown in (Eq. 2.4). As just indicated, most risk assessments produce several such sets of risk results. Once these sets are generated, they can be manipulated in various ways to display risk. The considerations and procedures used in the NUREG-1150 analyses to produce the sets shown in (Eq. 2.4) are the subject of this report.

Freq

≥ o

o: outcome
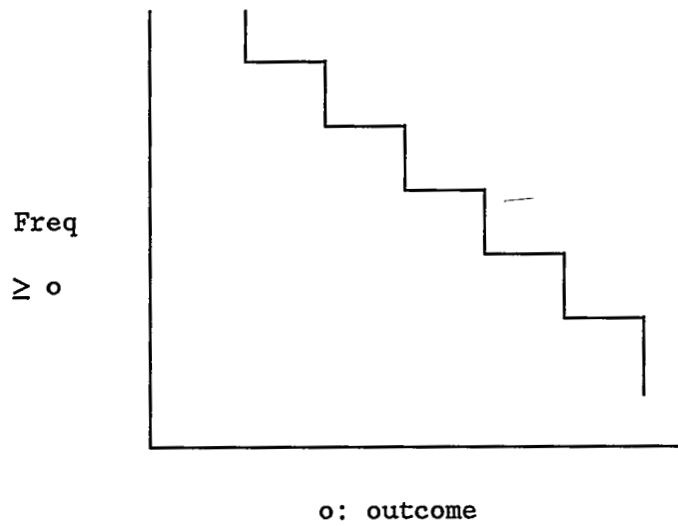
Figure 2-1.   Example Exceedance Frequency Curve.

2.2   References

1.   S. Kaplan and B. J. Garrick, "On the Quantitative Definition of Risk," Risk Analysis, 1: 11-27 (1981).

3.0 IDEAS UNDERLYING THE COMPUTATIONAL FRAMEWORK

As discussed in the introduction, the objectives of the NUREG-1150 analyses place a number of requirements on the computational procedures used to perform the analyses. In turn, these requirements lead to an analysis approach based on the following ideas:

- general and relatively fast-running models for the individual analysis components,

- well-defined interfaces between the individual analysis components,

- use of Monte Carlo techniques in conjunction with an efficient sampling procedure to propagate uncertainties,

- use of expert panels to develop distributions for important phenomenological issues,

- automation of the overall analysis.

Each of these ideas is discussed in more detail in the following sections.

3.1 General and Relatively Fast-Running Models

The integrated risk calculations performed for NUREG-1150 make use of general and relatively fast-running models for the individual analysis components. This approach is taken for several reasons.

First, computer models that could be evaluated quickly were needed because of the large variety of possible accidents that must be modeled. Accidents can be initiated in a variety of ways. Once an accident initiator occurs, there are many ways in which core damage might occur or be avoided. Given that core damage occurs, many different patterns of accident progression are possible in the primary system and in the containment. In turn, each of these patterns requires a source term estimate. Finally, each source term requires a consequence estimate.

The models used in the NUREG-1150 analyses had to be general in order to be applicable to the diverse accident conditions that arise. At present, it is neither practical nor possible to perform a detailed mechanistic calculation for every accident of interest. No current mechanistic code runs fast enough to permit a sufficient number of evaluations. Furthermore, no existing mechanistic code contains models for every important phenomena in reactor accidents that are generally accepted as adequate.

Second, these models provide a way to incorporate information from many sources into the NUREG-1150 analyses. These analyses attempt to use all available sources of information for each analysis component, including experimental data, past observational data, mechanistic modeling and, as appropriate or necessary, expert judgment. The use of general and parametric models provides a way to assemble and manipulate the information developed for each analysis component.

Specifically, the models do not represent physical processes in the manner that mechanistic reactor accident codes such as MELPROG,[1] STCP,[2] MELCOR[3] or CONTAIN[4] do. Rather, the PRA models used in NUREG-1150 provide a way to incorporate information obtained from mechanistic models of this type and from other sources into an analysis. For example, the accident progression model takes containment load pressure for each case as an input variable rather than calculating it; similarly, the source term model takes radionuclide release from fuel in the vessel under a specific set of conditions as an input variable rather than calculating it. These analysis methods provide a way to get information of the type just indicated into the analysis; the information itself comes from other sources.

Third, the NUREG-1150 plant studies use Monte Carlo techniques in the propagation and analysis of uncertainties. Such techniques require many repetitions of each plant study. Without fast-running models, it is not possible to perform the large number of required calculations.

The models used for the individual analysis components are now briefly considered. The accident frequency analyses were initially performed as part of the Accident Sequence Evaluation Program (ASEP) and are based on the extensive use of event and fault trees.[5] These analyses yielded minimal cut sets for each plant. These cut sets are used as the systems model in the integrated analysis. The TEMAC code[6,7] was developed to facilitate the manipulation and evaluation of these cut sets within the overall integrated analysis.

The accident progression analyses were performed with detailed accident progression event trees. These event trees contain a large number of questions with many of these questions having more than two outcomes. In these trees, the answer to a particular question can depend on answers to previous questions. These trees are used to combine the extensive experimental results and mechanistic code predictions to provide estimates of accident progression. The EVNTRE code[8] was developed to evaluate the accident progression event trees.

The estimates of the source term were made by relatively simple parametric models (or algorithms) that attempted to incorporate the results from detailed codes such as the STCP,[2,9] MELCOR,[3,10] MAAP,[11] and CONTAIN.[4] Due to the considerable cost and time requirements associated with running the detailed codes, it was possible to perform only a relatively small number of calculations for each plant with them. Therefore, it was necessary to estimate source terms for many scenarios that had not been expressly modeled. The parametric models developed for this purpose are collectively referred to as the XSOR codes:[12] the individual codes are SURSOR, SEQSOR, GGSOR, PBSOR, and ZISOR for the Surry, Sequoyah, Grand Gulf, Peach Bottom, and Zion analyses, respectively. These codes manipulate about 20 release parameters to obtain estimates of the source term for all types of accidents. Distributions for most of the parameters were determined by expert panels. Each individual expert based his distributions on the code results and experimental data that he felt were the most realistic, and modified his base distributions to account for processes and phenomena that were not included or that he felt were poorly modeled.

Consequence calculations were performed with the MACCS code.[13-15] MACCS is the most mechanistic of the codes used in the integrated risk calculations for

NUREG-1150. However, like the other codes used in the assembly process, it brings together information from many sources. Although uncertainties from the earlier parts of the analyses (i.e., systems analysis, accident progression analysis, and source term analysis) are propagated through the consequence calculations, no uncertainty in the consequence calculations is included (other than the stochastic variability due to weather). Since consequence modeling uncertainty was not considered, it was possible to use MACCS in the integrated analysis rather than a faster-running substitute.

3.2   Well-Defined Interfaces

To integrate the overall analysis for each plant, it is necessary to have well-defined interfaces between the constituent parts of the analysis. These interfaces serve several purposes: (1) To assure that consistent assumptions are used as the risk calculation progresses through the individual parts of an analysis, (2) to facilitate the calculation and display of intermediate results, (3) to provide traceability through the overall risk calculation, and (4) to reduce the number of calculations required in subsequent parts of the analysis.

The interfaces between individual analysis components are accomplished by the definition of groups of accidents from the previous analysis stage which provide similar sets of initial and boundary conditions for the next analysis stage. Specifically, the results of the accident frequency analysis are grouped into plant damage states for the subsequent accident progression analysis, where a plant damage state is a group of accidents that present a similar set of initial and boundary conditions to the accident progression analysis. The results of the accident progression analysis are grouped into accident progression bins for the source term analysis, where an accident progression bin is a group of accidents that present a similar set of initial and boundary conditions for the source term analysis. The results of the source term analysis are formed into source term groups for consequence analysis, where a source term group is a set of accidents that define similar conditions for the consequence analysis.

The use of consistent assumptions through an analysis is obtained by (1) defining the outcomes of accidents from a particular analysis stage (e.g., plant damage state characteristics from the systems analysis) so that they contain all the important conditions for the next analysis stage, and (2) assuring that parameters common to two or more analysis stages are assigned the same value. The number of required calculations is reduced since redundant calculations are eliminated by a grouping of accidents on the basis of the analysis conditions presented to the next analysis stage. The elimination of unnecessary calculations is essential since it would be computationally impractical to perform source term and consequence calculations for all possible accidents.

The use of plant damage states, accident progression bins, and source term groups to provide the interfaces between the individual parts of the integrated analysis leads to the following restatement of the expression in (Eq. 2.3) for offsite consequence risk:

$$rC_m = \sum_{j=1}^{nPDS} \sum_{k=1}^{nAPB} \sum_{l=1}^{nSTG} fPDS_j \, pAPB_{jk} \, pSTG_{kl} \, cSTG_{lm} \, , \qquad \text{(Eq. 3.1)}$$

3.3

where

rC_m = annual risk (units: consequences/yr) for consequence measure m (e.g., early fatalities),

$fPDS_j$ = frequency (units = yr^{-1}) of plant damage state j

$pAPB_{jk}$ = probability that plant damage state j will result in accident progression bin k,

$pSTG_{kl}$ = probability that accident progression bin k will be assigned to source term group l ($pSTG_{kl} = 1$ if accident progression bin k is assigned to source term group l and $pSTG_{kl} = 0$ otherwise),

$cSTG_{lm}$ = mean (over weather variability) for consequence measure m (units: as appropriate for consequence measure m) conditional on the occurrence of source term group l,

and nPDS, nAPB, and nSTG are the number of plant damage states, accident progression bins and source term groups, respectively. More detailed risk results (i.e., exceedance frequency curves) are also possible by using the consequence results generated for individual weather sequences. The use of well-defined interfaces facilitates both traceability and the calculation of intermediate results or outcomes. As can be seen from the preceding summation, the interfaces allow a calculation to be followed through the individual parts of the analysis. Further, by stopping before consequence results, it is possible to obtain intermediate results.

As discussed in Chapter 2 and shown in (Eq. 2.4), the NUREG-1150 analyses use a representation for risk based on sets of triples of the form

$$R = \{ (S_i, f_i, o_i), i=1, \ldots nS \} , \qquad \text{(Eq. 3.2)}$$

where S_i is a scenario (i.e. set of accidents), f_i is the frequency for S_i, o_i is the vector of outcomes associated with S_i, and nS is the number of scenarios. The representation for annual offsite consequence risk in (Eq. 3.1) is the result of choosing the S_i's to be source term groups, the f_i's to be the frequency of these groups, and the o_i's to be the mean (over weather variability) consequence results associated with these groups. However, the interfaces discussed in this section give rise to many additional ways in which the set R might be defined. Some of these ways will be discussed in Chapter 4.

3.3   Monte Carlo Techniques

Early in the NUREG-1150 analyses, several alternative techniques for the propagation and analysis of uncertainty were considered: the OCP approach (i.e., propagation of optimistic, central, and pessimistic assumptions), differential analysis,[16] response surface methodology,[17] Monte Carlo analysis,[18] propagation of discrete probability distributions,[19] the Maximus methodology,[20] Kalman filtering,[21] and the Fourier amplitude sensitivity test.[22]   Comparative discussions of these techniques can be found in various reviews.[23-29] As indicated in the next three paragraphs, most of these methods did not seem to be appropriate for an analysis of the type and scale necessary to integrate the four parts of the NUREG-1150 analyses.

The OCP approach is based on performing three analyses: one with optimistic assumptions, one with central assumptions, and one with pessimistic assumptions. The spread in the outcomes of these analyses then provides a measure of uncertainty. This approach was tried early in the NUREG-1150 analyses. It was not used extensively, however, because the systematic compounding of optimistic results and the systematic compounding of pessimistic results produced an extreme representation of upper and lower bounds for risk. Further, it did not provide a means to perform sensitivity analyses.

Differential analysis is based on developing a Taylor series approximation to a model and then using this approximation in uncertainty and sensitivity studies. Due to the complexity of the individual and assembled parts of the NUREG-1150 analyses, the large uncertainties involved, and the existence of discontinuities, an approach based on differential techniques did not seem to be practicable. Response surface methodology is based on using classical experimental designs in the development of response surface replacements for models and then using these replacements as surrogates for the original models in subsequent uncertainty and sensitivity studies. Due to the scale of the analysis, the different possible regimes of model behavior, the complexity of the individual models, and the large uncertainties involved, the use of response surface methodology did not seem to provide a viable approach to uncertainty and sensitivity analysis in the integrated analysis. Although propagation of discrete probability distributions does yield uncertainty information, it does not provide a means of performing sensitivity analyses. It is also very cumbersome for large numbers of variables.

The Maximus methodology provides a means of propagating binomial and Poisson failure data; however, it was not designed for the much broader range of uncertainty and sensitivity issues that must be treated in a fully integrated probabilistic risk assessment. The Fourier amplitude sensitivity test is based on using a Fourier series to approximate a model. Like differential analysis and response surface methodology, it is not appropriate for use in analyses as complex as a fully integrated probabilistic risk assessment. Finally, Kalman filtering involves techniques for relating observations of the past behavior of a process and a model of that process to the uncertainty in predictions of the future behavior of the process. As such, Kalman filtering is not appropriate for uncertainty problems of the type encountered in integrating the NUREG-1150 analyses.

However, techniques based on Monte Carlo procedures were found to provide a suitable approach to uncertainty propagation. This approach to uncertainty propagation meshes very well with the already indicated approach to risk calculation based on relatively fast-running models and well-defined interfaces between the individual analysis parts. Monte Carlo simulation creates a mapping from analysis assumptions to analysis results. Once this mapping is created, it can be studied with a variety of techniques (e.g., scatterplots, distribution functions, regression analysis, partial correlation analysis). Unlike differential analysis and response surface methodology, this mapping does not involve any intermediate filters (i.e., Taylor series and response surfaces) that smooth and obscure discontinuities and transitions between regimes of behavior. Monte Carlo techniques allow the consideration of essentially any variable that can be supplied to a model as input or generated as an output. Further, Monte Carlo techniques will operate in the presence of large uncertainties and discontinuities, although discontinuities and multiple regimes of behavior always complicate sensitivity studies. However, as it provides a means to identify these situations, Monte Carlo simulation is superior to other techniques when such complications exist. Since Monte Carlo simulation is sampling-based, it is possible to include variables with wide ranges and also to incorporate correlations between variables.

Computational cost is always a concern when Monte Carlo techniques are used in a complex analysis. In the NUREG-1150 analyses, computational cost is controlled by using (1) relatively fast-running models as means of incorporating results obtained with more detailed models into the analysis, (2) well-defined model interfaces to eliminate redundant calculations, and (3) an efficient sampling technique (i.e., Latin hypercube sampling[30]).

Uncertainty propagation is accomplished by generating a Latin hypercube sample from the parameters selected for uncertainty analysis and then propagating this sample through the risk calculations. Specifically, generation of this sample yields a sequence of sample elements of the form

$$X_s = [X_{s1}, X_{s2}, \ldots, X_{s,nV}] \ , \ s = 1, 2, \ldots, nLHS , \qquad \text{(Eq. 3.3)}$$

where X_{st} is the value for sampled variable X_t in sample element s, nV is the number of variables selected for the study, and nLHS is the number of sample elements.

A complete risk calculation is performed for each sample element. This yields a sequence of risk results of the form

$$rC_{sm} = \sum_{j=1}^{nPDS} \sum_{k=1}^{nAPB} \sum_{l=1}^{nSTG} fPDS_{sj} \, pAPB_{sjk} \, pSTG_{skl} \, cSTG_{lm} , \qquad \text{(Eq. 3.4)}$$

where variables are defined the same as in (Eq. 3.1) with the addition of the subscript s to indicate dependency on the sample element X_s. The annual risk results indicated in (Eq. 2.3) as well as other intermediate and conditional results are then available for uncertainty and sensitivity analysis. More

generally, the result is a sequence of sets R_s, s=1,... nLHS, of the form shown in (Eq. 2.4). Each R_s is the result of a complete risk assessment performed with a consistent set of input parameters and analysis assumptions as defined by X_s. The risk results defined by these sets can be displayed and compared in many ways to assess the impact of uncertainty in important analysis parameters and assumptions.

3.4 Use of Expert Panels

As already indicated, the NUREG-1150 analyses attempted to make use of information from all available sources. A quantitative indication of the effects of uncertainties in important analysis parameters on risk was also desired.

To obtain broad distributions for analysis parameters that reflected all the extant schools of thought, panels of outside experts from diverse organizations were formed in specific areas (e.g., structural response, source term estimation). These panels had two purposes. The first was to ensure that all available information relevant to the NUREG-1150 analyses was recognized and incorporated into the individual plant studies. The second was to develop probability distributions for the most important parameters used in the NUREG-1150 analyses. Individuals from the nuclear industry, the national laboratories, and academia served on these panels.

The expert panels were used to characterize the uncertainty in parameters used in the accident frequency analysis, accident progression analysis and source term analysis. The parameters considered by these panels were selected through interactions between the expert panels and the NUREG-1150 analyses staff. Considerations in the selection of parameters included uncertainty in the parameter, anticipated contribution to uncertainty in risk, and interest within the reactor safety community. As previously indicated, the uncertainty in the parameters used in the consequence analysis was not assessed.

The review process led to the characterization of the uncertainty in over 100 parameters for each plant study. The effect of this uncertainty was determined by generating a Latin hypercube sample for the parameters for each plant and then propagating the elements of this sample through the integrated analysis as indicated in (Eq. 3.4).

3.5 Automation of Overall Analysis

Both to expedite the overall analysis and to reduce the potential for errors, it is necessary to automate the analysis process. At the center of this automation are the fast-running models developed for the individual parts of the overall analysis and the well-defined interfaces between the parts. Automation is accomplished within a structure of the form shown in Figure 3-1. Each model produces a specified set of outputs which is written to a file. Some of this output is needed for generating input to the next analysis stage and some is available for evaluation at that point in the analysis with no further use in subsequent parts of the analysis. Input to the next analysis stage is generated by a postprocessor which reads the output file generated by the previous analysis stage and prepares the input necessary for the next stage. A more detailed

discussion of the flow of information from one set of codes to another in the calculation of risk is presented in Appendix A of this volume. An example of a calculation all the way through all the constituent analyses may be found in NUREG-1150, Vol. 2, Appendix B.

By reducing the amount of human intervention required at the analysis interfaces, quality control is greatly enhanced. Further, by saving detailed analysis results at each interface, two other requirements of the NUREG-1150 analyses are satisfied. First, it is possible to trace the calculation of individual results through the entire analysis. Second, it is possible to produce summary results at different levels of detail.

A number of programs were developed to manipulate the results of the NUREG-1150 studies. For example, the RISQUE or PRAMIS[31] codes can be used to produce and analyze annual risk results of the form shown in (Eq. 3.1) and (Eq. 3.4). (RISQUE is described in Appendix B of this volume.) In essence, the analysis procedure used in NUREG-1150 produces a mapping from analysis input to analysis results. Once generated, this mapping can be manipulated and studied in many ways.

ACCIDENT
FREQUENCY
ANALYSIS

ACCIDENT
PROGRESSION
ANALYSIS

SOURCE TERM
ANALYSIS

CONSEQUENCE
ANALYSIS

event tree
models

Accident Progression
event tree

Magnitudes
of all source
terms calculated

Accident
progression
bin
characteristics

SETS[32]

EVNTRE[8]

PSTEVNT[33]

XSOR[12]

PARTITION[34]

Core damage
cutset
expressions

Source term group
characteristics
and
mapping of accident
progression bins
to source term groups

TEMAC[6]

Probabilities of
accident progression
bins for each plant
damage state

Source term magnitudes
and release information
for each accident
progression bin

MACCS[13-15]

Frequencies of
plant damage
states

Probabilities
of consequense
measures for
each source term
group

fIE P (IE-->PDS)   P (PDS-->APB)   P (APB-->STG)   C = RISK

RISQUE – PRAMIS[31]

Figure 3-1.   Relationship of the computer codes used in the risk analyses
for NUREG-1150 (see references 6, 8, 12-15, and 31-34).

3.9

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4.0 STRUCTURE OF THE NUREG-1150 PLANT STUDIES

The preceding chapter discussed the main ideas that underlie the computational framework used for the individual plant studies in NUREG-1150. The purpose of this section is to give a mathematical description of this structure and to introduce notation that will be used throughout this report to describe the computations performed in the individual plant studies.

The NUREG-1150 plant studies are fully integrated Level III probabilistic risk assessments; the calculations leading to both risk and uncertainty in risk are carried through all four constituent analyses as shown in Figure 4-1. The calculation of risk proceeds in a manner whereby the effects of each initiating event are traced directly through the entire analysis to arrive at a number of specific consequences. In Figure 4-1 each distinct continuous line that can be followed from the left of the illustration to the box marked "Risk Calculation" corresponds to a distinct group of accidents with a particular set of characteristics in each analysis step.

As shown in (Eq. 3.1), the calculation of annual offsite consequence risk can be represented by a triple summation. Each summation corresponds to one of the three interfaces shown in Figure 4-1. Further, the term in the overall summation is the product of four factors, one from each of the analysis components. Although (Eq. 3.1) provides a correct expression of the manner in which annual risk is calculated in the NUREG-1150 analyses, it is not very compact or easy to read. Further, it does not readily lend itself to the calculation of intermediate or conditional results. A representation based on a matrix formalism[1,2] provides a natural way to summarize the computations performed in the individual analysis components and to display the interfaces between the components. Further, it makes it easy to visualize and implement calculations that produce intermediate and conditional results.

In this section, a matrix representation for the assembly of the NUREG-1150 analyses will be described. In addition, this representation will be used to illustrate different ways in which the set R of risk results given in (Eq. 2.4) can be defined.

4.1 Accident Frequency Analysis

The accident frequency analysis uses event tree and fault tree techniques to identify the combinations of events that can lead to core damage and to estimate their frequencies of occurrence. On a system level, these combinations of events are denoted "sequences". On an individual fault level (e.g., failures of specific pumps and valves), these combinations of events are called "cut sets". The cut sets of interest are those which contain no more faults than those required to cause core damage. These cut sets are denoted "minimal cut sets". The cut sets are identified by means of fault trees, and the minimal cut sets are sorted into accident sequences by means of event trees. The frequency of an accident sequence is obtained by combining the frequency of the initiating event with the sum of the probabilities of all the minimal cut sets in the sequence.

4.1
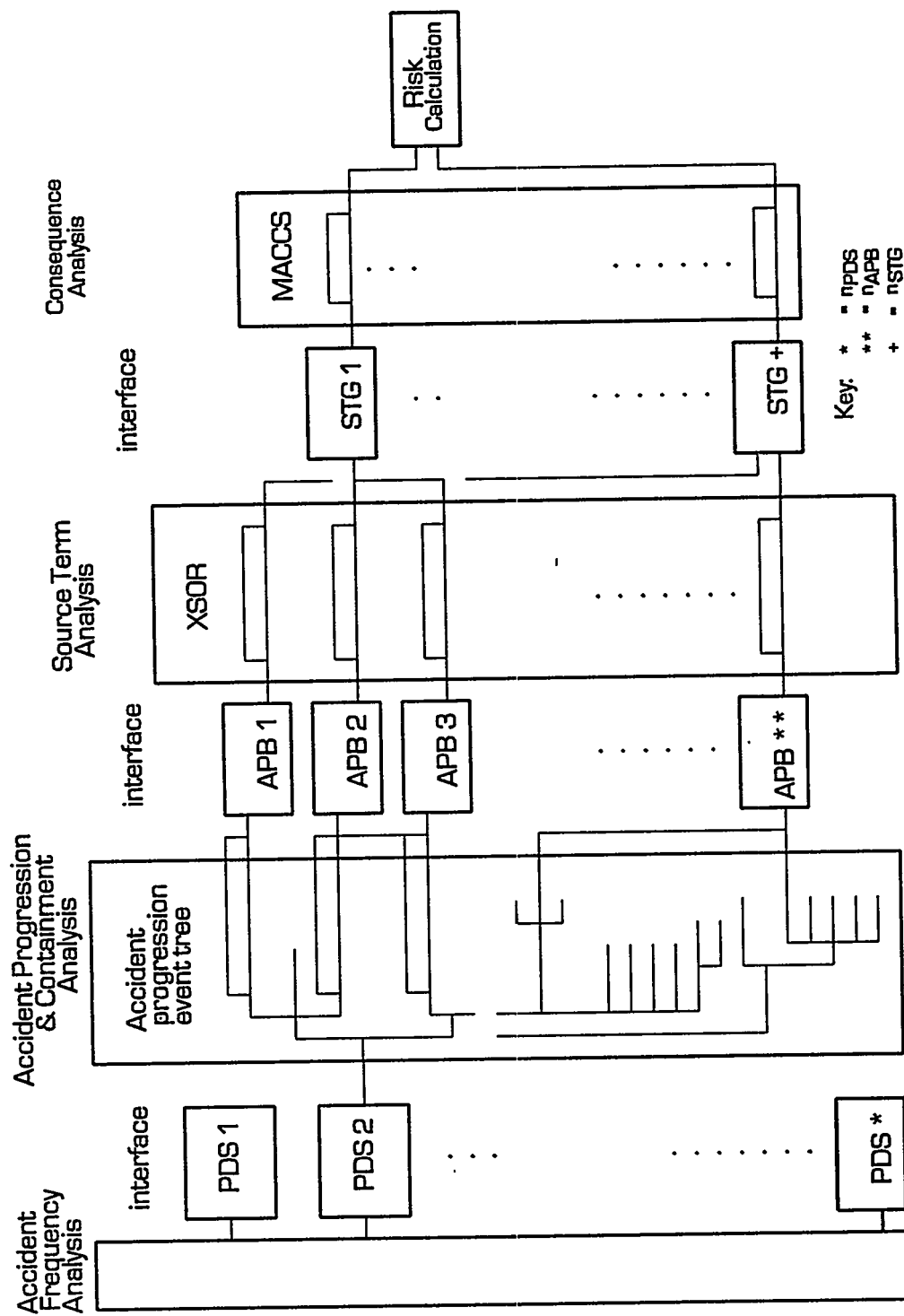
Figure 4-1 Risk analysis parts and interfaces.

In order to pass information forward to the accident progression analysis, accident sequences are grouped into plant damage states (PDSs). Each PDS is a group of accidents that provide a similar set of initial and boundary conditions for the subsequent accident progression analysis. The plant damage states form the interface between the accident frequency analysis and the accident progression analysis. The frequency of a plant damage state is the sum of the frequencies of the accident sequences that it contains. In some cases the definition of the PDSs did not correspond exactly to the accident sequence definitions so that it was necessary to place some minimal cut sets from a sequence in one PDS and the remaining minimal cut sets in another PDS. By removing the frequency of the initiating event from each accident sequence or minimal cut set, the conditional probabilities of the plant damage states given the occurrence of individual initiating events can also be obtained.

When the frequencies of the initiating events and the conditional probabilities of the plant damage states are separated, the matrix representation for the systems analysis has the form

$$fPDS = fIE \; P(IE \rightarrow PDS) \; , \qquad \text{(Eq. 4.1)}$$

where $fPDS$ is the vector of frequencies for the plant damage states, fIE is the vector of frequencies for the initiating events, and $P(IE \rightarrow PDS)$ is the matrix of transition probabilities from initiating events to plant damage states. Specifically,

$$fIE = [fIE_1, \ldots, fIE_{nIE}],$$

fIE_i = frequency per year for initiating event i,

nIE = number of initiating events,

$$fPDS = [fPDS_1, \ldots, fPDS_{nPDS}],$$

$fPDS_j$ = frequency per year for plant damage state j,

$nPDS$ = number of plant damage states,

$$P(IE \rightarrow PDS) = \begin{bmatrix} pPDS_{11} & \cdots & pPDS_{1,nPDS} \\ \vdots & & \\ pPDS_{nIE,1} & \cdots & pPDS_{nIE,nPDS} \end{bmatrix}$$

and

$pPDS_{ij}$ = probability that initiating event i will lead to plant damage state j.

4.3

The elements $pPDS_{ij}$ of $P(IE \rightarrow PDS)$ are conditional probabilities: given that initiating event i has occurred, $pPDS_{ij}$ is the probability that plant damage state j will also result.

The elements of $P(IE \rightarrow PDS)$ are determined in the analysis of the previously indicated minimal cut sets with the TEMAC[3] program. In turn, both the cut sets and the data used in their analysis come from earlier studies that draw on many sources of information. Thus, the elements $pPDS_{ij}$ of $P(IE \rightarrow PDS)$ are, in reality, functions of the many sources of information that went into the systems analysis.

Chapter 2 introduced the idea that risk can be viewed as a set $R = \{(S_i, f_i, o_i), i = 1, ..., nS\}$ of ordered triples of the form shown in (Eq. 2.4). There are many ways in which R can be defined within a probabilistic risk assessment. One way is to let S_i be all accidents assigned to plant damage state i, f_i be $fPDS_i$, and o_i be the status of the engineered safety systems important to accident progression given that plant damage state i has occurred.

Specific examples of such representations of results in NUREG-1150[4] and additional information on the structure and performance of the accident frequency analysis are given in Chapter 5.

4.2   Accident Progression and Containment Response Analysis

The accident progression analysis uses event tree techniques to determine the possible ways in which an accident might evolve from each plant damage state. Specifically, a single event tree is developed for each plant and evaluated with the EVNTRE[5] computer program. The development and quantification of each event tree is based on past observational data, experimental data, mechanistic code calculations, and expert judgement.

The characterizations for the individual plant damage states provide enough information to answer a set of initial condition questions in the accident progression event trees. The branch probabilities specified for these initial condition questions provide the link between the systems analysis and the accident progression analysis.

Due to the large number of questions in the NUREG-1150 accident progression event trees and the fact that many of these questions have more than two branches, there are far too many paths through each tree to permit each path to be considered in the subsequent source term and consequence analysis. Therefore, the paths through the trees are grouped into accident progression bins, where each bin is a group of paths through the event tree that define a similar set of initial and boundary conditions for source term analysis.

The transition matrix representation used for the systems analysis can also be used to summarize the accident progression analysis. For the accident progression analysis, this representation has the form

$$fAPB = fPDS \; P(PDS \rightarrow APB) \; , \qquad \text{(Eq. 4.2)}$$

where fPDS is the vector of frequencies for the plant damage states defined in (Eq. 4.1), fAPB is the vector of frequencies for the accident progression bins, and P(PDS→APB) is the matrix of transition probabilities from plant damage states to accident progression bins. Specifically,

$$\text{fAPB} = [\text{fAPB}_1, \ldots, \text{fAPB}_{nAPB}]$$

$$\text{fAPB}_k = \text{frequency per year for accident progression bin k,}$$

$$\text{nAPB} = \text{number of accident progression bins,}$$

$$P(PDS{\rightarrow}APB) = \begin{bmatrix} pAPB_{11} & \cdots & pAPB_{1,nAPB} \\ \cdot & & \\ \cdot & & \\ \cdot & & \\ pAPB_{nPDS,1} & \cdots & pAPB_{nPDS,nAPB} \end{bmatrix}$$

and

$$pAPB_{jk} = \text{probability that plant damage state j will lead to accident progression bin k.}$$

The properties of fPDS are given in conjunction with (Eq. 4.1). The elements $pAPB_{jk}$ of P(PDS→APB) are determined in the accident progression analysis with EVNTRE for the individual plant damage states.

Additional ways in which the set R = {(S_i, f_i, o_i)} introduced in (Eq. 2.4) might be defined are possible at this point in the analysis. One way would be to let each S_i be all accidents assigned to accident progression bin i, f_i be $fAPB_i$, and o_i be the vector of attributes associated with the accident progression bin i that will be used as input to the source term analysis. Another way to define R would be to let each S_i be all accidents assigned to plant damage state i, f_i be $fPDS_i$, and o_i be the matrix, [$pAPB_{i1}, \ldots .pAPB_{i,nAPB}$].

Specific examples of such representation of results and additional information on the structure and performance of the accident progression analysis are given in Chapter 6 and in the plant volumes of this report.[6-10]

4.3 Source Term Analysis

As in the systems analysis and the accident progression analysis, the source term analysis draws on many sources of information. The information from these sources was assembled in the context of the integrated NUREG-1150 analyses with relatively simple parametric models implemented in the XSOR programs.[11] The XSOR programs provided a source term estimate for each accident progression bin identified in the accident progression analyses.

A large number of accident progression bins were identified in the integrated analysis for each plant and the consequence model used required considerably more computer resources per evaluation than the XSOR programs. Thus, it was not practical to perform a consequence calculation for every source term. Therefore,

to form an interface between the source term analysis and the consequence analysis, the source terms estimated in the source term analysis were combined into source term groups, where each group is a collection of source terms that define similar conditions for consequence analysis.

The transition matrix representation can be continued for the source term analysis and takes the form

$$fSTG = fAPB \; P(APB \rightarrow STG) \; , \qquad\qquad (Eq. \; 4.3)$$

where fAPB is the vector of frequencies for the accident progression bins defined in (Eq. 4.2), fSTG is the vector of frequencies for the source term groups, and P(APB→STG) is the matrix of transition probabilities from accident progression bins to source term groups. Specifically,

$$STG = [fSTG_1, \; \ldots, \; fSTG_{nSTG}],$$

$fSTG_{k1}$ = frequency per year for source term group 1,

nSTG = number of source term groups,

$$P(APB \rightarrow STG) = \begin{bmatrix} pSTG_{11} & \cdots & pSTG_{1,nAPB} \\ \vdots & & \\ pSTG_{nAPB,1} & \cdots & pSTG_{nAPB,nSTG} \end{bmatrix}$$

and

$pSTG_{k1}$ = probability that accident progression bin k will be assigned to source term group 1.

= 1 if accident progression bin k is assigned to source term group 1

= 0 otherwise.

The elements of the matrix P(APB→STG) are generated by the PARTITION[12] code. PARTITION also generates a mean source term for each source term group. These mean source terms are used in the subsequent consequence calculations. The properties of fAPB are given in conjunction with (Eq. 4.2).

Completion of the source term analysis provides additional ways in which the set R = {(S_i, f_i, o_i)} given in (Eq. 2.4) might be defined. One way would be to let each S_i be all accidents assigned to accident progression bin i, f_i be $fAPB_i$, and o_i be the source term associated with the accident progression bin i. Release fractions for radionuclides with similar chemical properties are among the results included in a source term. Since release fractions can be ordered by size, it is possible to use this representation for risk to generate exceedance frequency curves of the form shown in Figure 2-1, where release fraction size for a group of radionuclides would appear on the abscissa and the frequency at which

release fractions of a given size were exceeded would appear on the ordinate. Another way to define R would be to let each S_i be all accidents assigned to a source term group, f_i be $fSTG_i$, and o_i be the mean source term for the source term group calculated by PARTITION.

Specific examples of such representations of results and additional information on the structure and performance of the source term analysis is given in Chapter 7, Reference 6, and in the plant volumes of this report.[6-10]

4.4 Consequence Analysis

The source term analysis and the subsequent formation of source term groups is followed by the consequence analysis. This analysis component uses the MACCS[13-15] program to estimate various consequence measures for each source term group. The results for each group include estimates for both mean consequences and distributions of consequences. The indicated means and distributions result from uncertainty as to the weather conditions that will exist at the time of an accident and are conditional on the occurrence of each source term group. The results of the consequence analysis can be used to develop two different, though related, representations for risk: annual risk (units: consequence/yr) and exceedance frequencies for individual consequence values.

When the transition matrix formalism is used, the representation for annual risk becomes

$$rC = fSTG \ cSTG , \qquad \text{(Eq. 4.4)}$$

where $fSTG$ is the vector of frequencies for the source term groups defined in (Eq. 4.3), rC is the vector of risk measures, and $cSTG$ is the matrix of mean consequence measures conditional on the occurrence of individual source term groups. Specifically,

$rC \qquad = \quad [rC_1, \ldots, rC_{nC}],$

$rC_m \qquad = \quad$ risk (consequence per year) for consequence measure m,

$nC \qquad = \quad$ number of consequence measures,

$$cSTG = \begin{bmatrix} cSTG_{11} & \cdots & cSTG_{1,nC} \\ \cdot & & \\ \cdot & & \\ \cdot & & \\ cSTG_{nSTG,1} & \cdots & cSTG_{nSTG,nC} \end{bmatrix}$$

4.7

and

$cSTG_{1m}$ = mean value (over weather) of consequence measure m conditional on the occurrence of source term group 1.

The properties of fSTG are given in conjunction with (Eq. 4.3). The elements $cSTG_{1m}$ of cSTG are determined from consequence calculations with MACCS for individual source term groups.

The equations (Eq. 4.1) through (Eq. 4.4) can be combined to obtain the following representation for annual consequence risk:

$$rC = fIE \; P(IE \rightarrow PDS) \; P(PDS \rightarrow APB) \; P(APB \rightarrow STG) \; cSTG \qquad (Eq.4.5)$$

This equation is (Eq. 3.1) expanded to show the frequency of the initiating events explicitly and written in matrix notation. It illustrates how the integrated analysis propagates from the initiating event frequencies all the way through to consequence risk measures.

The results of the consequence analysis can also be used to obtain exceedance frequencies for individual consequence values. The actual outcome of the consequence analysis for source term group 1 and consequence measure m is a sequence of values of the form $(pW_n, cSTG_{1mn})$, n= 1,...,nW, where

pW_n = probability of occurrence for weather trial n,

$cSTG_{1mn}$ = consequence value associated with source term group 1, consequence measure m, and weather trial n, and

nW = number of weather trials.

In MACCS, the number of weather trials depends on the number of weather categories in use, the number of samples per weather category, and the number of wind directions considered.

As already shown, the integrated analysis associates a frequency $fSTG_1$ with each source term group. Once the frequencies $fSTG_1$ and the sequences $(pW_n, cSTG_{1mn})$, n=1,...,nW, are known, an exceedance frequency curve of the form shown in Figure 4-2 can be constructed for consequence measure m. Such curves consist of a locus of points of the form (c,f), where c is a consequence value and f is the frequency (per year) at which a consequence value as large or larger than c results due to an accident at the plant under consideration.
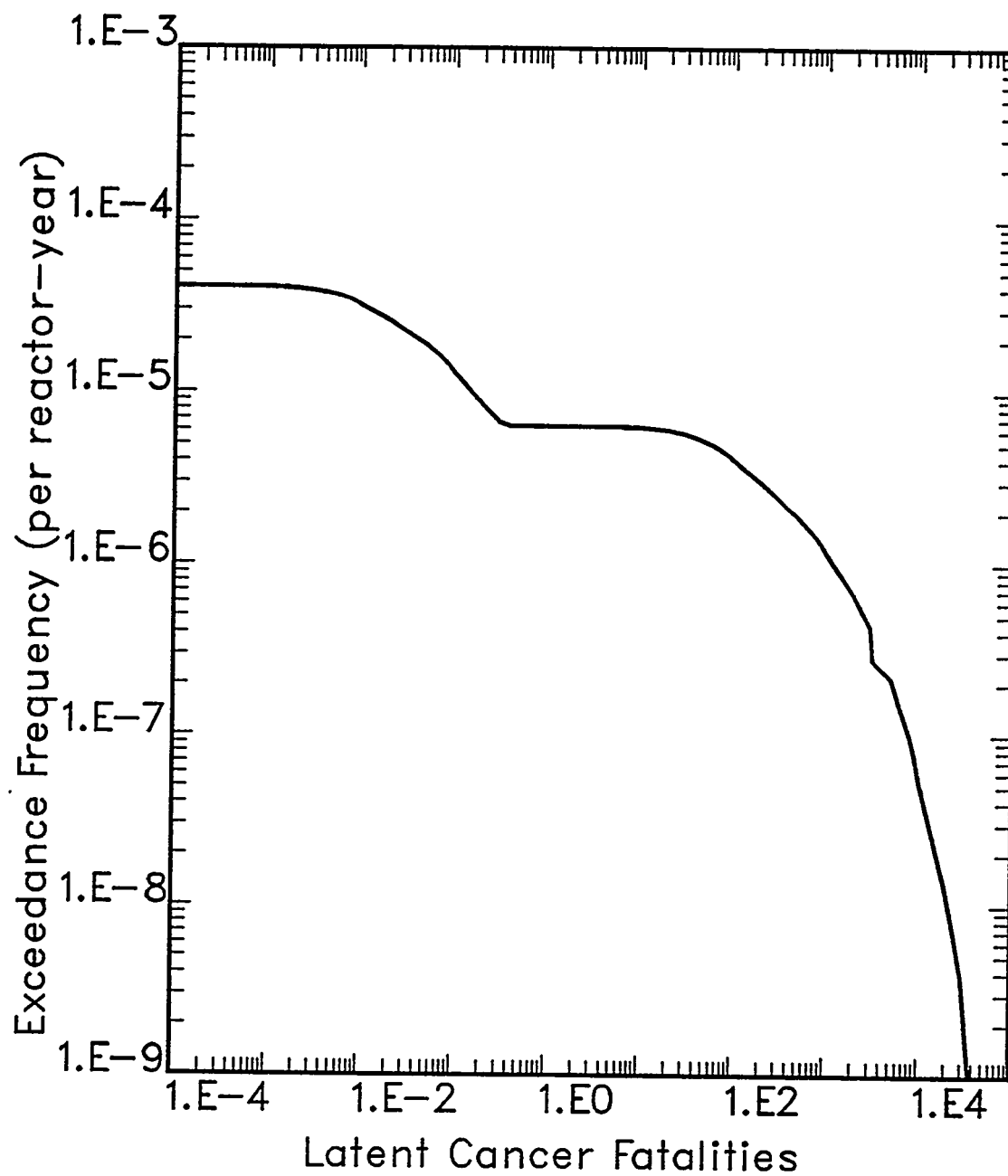
Figure 4-2 Example exceedance frequency curve.

The representation of risk as a set R = {(S_i, f_i, o_i)} of the form defined in (Eq. 2.4) is also applicable to the results of the consequence analysis. One possibility is to let S_i be source term group i, f_i be $fSTG_i$, and o_i = [$cSTG_{i1}$, ..., $cSTG_{i,nc}$]. In this case, the calculation of annual consequence risks as shown in (Eq. 4.4) is equivalent to the calculation shown in (Eq. 2.3). Another possibility is to let S_i represent all accidents in a particular source term group l that involve the occurrence of a particular weather trial (i.e., n), f_i = $fSTG_l$ pW_n, and o_i = [$cSTG_{l,1,n}$, ..., $cSTG_{l,nc,n}$]. The use of this representation yields exceedance frequency curves of the form shown in Figure 4-2.

Specific examples of such representations of results and additional information on the performance and structure of the consequence analysis is given in Chapter 8, Volume 2, Part 7 of this report.[16]

4.5   Propagation of Uncertainties

The integrated NUREG-1150 analyses use Monte Carlo procedures as a basis for both uncertainty and sensitivity analysis. With this approach, a sequence

$$X_1, X_2, \ldots, X_{nV} \qquad \text{(Eq. 4.6)}$$

of nV potentially important variables is identified for use in uncertainty and sensitivity analysis. Then, expert review panels are used to assess the uncertainty in these variables[17-21] and formal decision analysis techniques[22] are used to aggregate the assessments of the individual panel members into a sequence of distributions

$$D_1, D_2, \ldots, D_{nV}, \qquad \text{(Eq. 4.7)}$$

where D_t is the distribution assigned to variable X_t.   Then, the Latin hypercube sampling program[23] is used to obtain the variable values that will actually be propagated through the integrated analysis. The result of generating a sample from the variables in (Eq. 4.6) with the distributions in (Eq. 4.7) is a vector

$$X_s = [X_{s1}, X_{s2}, \ldots, X_{s,nV}], \ s = 1, 2, \ldots, nLHS \qquad \text{(Eq. 4.8)}$$

of sample elements, where X_{st} is the value for variable X_t in sample element s and nLHS is the number of sample elements. The expression in (Eq. 4.5) is determined for each element of the sample. This creates a sequence of results of the form

$$\begin{aligned} rC_s &= fIE_s \, P_s(IE \to PDS) \, P_s(PDS \to APB) \, P_s(APB \to STG) \, cSTG \\ &= fPDS_s \, P_s(PDS \to APB) \, P_s(APB \to STG) \, cSTG, \end{aligned} \qquad \text{(Eq.4.9)}$$

where the subscript s is used to denote the evaluation of the expression in (Eq. 4.5) with sample element s in (Eq. 4.8). The uncertainty and sensitivity analyses in NUREG-1150 for annual risk results are based on the calculations summarized in (Eq. 4.9). Since fPDS, P(PDS→APB) and P(APB→STG) are based on

4.10

results obtained with TEMAC[3], EVNTRE[5] and the appropriate XSOR[11] program, determination of the expression in (Eq. 4.9) requires the use of these models with each sample element. The matrix cSTG in (Eq. 4.9) is not subscripted because the NUREG-1150 analyses do not include consequence modeling uncertainty (other than stochastic variability due to weather conditions).

Figure 4-3 shows an expanded version of (Eq. 4.9). The large number of parameters to be determined and manipulated in the risk calculations becomes evident when the matrices are explicitly written out, as in this figure.

The results obtained from (Eq. 4.9) can be summarized with either a probability density function or a cumulative distribution function. The construction of exceedance frequency curves (see Chapter 2) can also be repeated for each sample element. This leads to families of curves of the form shown in Figure 4-4. Each curve in these families arises from one sample element. Taken as a whole, such families can be viewed as a representation for the uncertainty in the estimation of the exceedance frequencies for a given consequence measure. They can also be used as input to sensitivity studies.

As discussed in Section 2.2, the most basic way to represent the risk results obtained in the NUREG-1150 analyses is with sets R of ordered triples. A number of ways in which such sets might be defined have been illustrated in this section. When the sample indicated in (Eq. 4.6) is propagated through a plant study, a set R_s is obtained for each sample element X_s. These sets are of the form

$$R_s = \{ (S_{si}, f_{si}, o_{si}), i = 1, \ldots, nS_s, \} \qquad \text{(Eq. 4.10)}$$

where there is now a set, S_{si}, of accident groupings, a sum of frequencies of the accidents, f_{si}, and a vector of outcomes, o_{si}, generated for each sample element X_s. Each set R_s is the result of a complete risk study performed with a consistent set of assumptions defined by X_s. Annual risks, exceedance frequency curves and other results selected for the representation of risk can be generated for each R_s. The variability in these results over the set R_s provides the uncertainty analysis results presented in the NUREG-1150 plant studies. The assessment of the causes of this variability provide the sensitivity analysis results presented in the NUREG-1150 plant studies.

There are two types of uncertainties that enter into the results of the NUREG-1150 probabilistic risk assessments. The first type of uncertainty derives from the stochastic or random nature of events. In such cases, it is known that, given a specific set of conditions, an event has nonzero probabilities of both occurrence and non-occurrence. If these occurrence probabilities are known with high accuracy, then this event does not introduce uncertainty into the final

Accident Frequency Analysis	Accident Progression Analysis	Source Term Analysis	Consequence Analysis	Risk Results
LHS#1 $f(PDS)$	$P(PDS \to APB)$	$P(APB \to STG)$	$C(STG)$	RISK

$$[f_1 \ldots f_{n_{PDS}}] \quad \times \quad \begin{bmatrix} P_{11} & P_{12} \ldots P_{1n_{APB}} \\ P_{21} & \\ \cdot & \\ \cdot & \\ \cdot & \\ P_{n_{PDS}}1 & \ldots P_{n_{PDS}}n_{APB} \end{bmatrix} \quad \times \quad \begin{bmatrix} P_{11} & P_{12} \ldots P_{1n_{STG}} \\ P_{21} & \\ \cdot & \\ \cdot & \\ \cdot & \\ P_{n_{APB}}1 & \ldots P_{n_{APB}}n_{STG} \end{bmatrix} \quad \times \quad \begin{bmatrix} C_{11} & C_{12} \ldots C_{1n_c} \\ C_{21} & \\ \cdot & \\ \cdot & \\ \cdot & \\ C_{n_{STG}}1 & \ldots P_{n_{STG}}n_c \end{bmatrix} \quad = [RISK_1 \ldots RISK_{n_c}]$$

Accident Frequency Analysis	Accident Progression Analysis	Source Term Analysis	Consequence Analysis	Risk Results
LHS#2 $f(PDS)$	$P(PDS \to APB)$	$P(APB \to STG)$	$C(STG)$	RISK

$$[f_1 \ldots f_{n_{PDS}}] \quad \times \quad \begin{bmatrix} P_{11} & P_{12} \ldots P_{1n_{APB}} \\ P_{21} & \\ \cdot & \\ \cdot & \\ \cdot & \\ P_{n_{PDS}}1 & \ldots P_{n_{PDS}}n_{APB} \end{bmatrix} \quad \times \quad \begin{bmatrix} P_{11} & P_{12} \ldots P_{1n_{STG}} \\ P_{21} & \\ \cdot & \\ \cdot & \\ \cdot & \\ P_{n_{APB}}1 & \ldots P_{n_{APB}}n_{STG} \end{bmatrix} \quad \times \quad \begin{bmatrix} C_{11} & C_{12} \ldots C_{1n_c} \\ C_{21} & \\ \cdot & \\ \cdot & \\ \cdot & \\ C_{n_{STG}}1 & \ldots P_{n_{STG}}n_c \end{bmatrix} \quad = [RISK_1 \ldots RISK_{n_c}]$$

Accident Frequency Analysis	Accident Progression Analysis	Source Term Analysis	Consequence Analysis	Risk Results
LHS#n_{LHS} $f(PDS)$	$P(PDS \to APB)$	$P(APB \to STG)$	$C(STG)$	RISK

$$[f_1 \ldots f_{n_{PDS}}] \quad \times \quad \begin{bmatrix} P_{11} & P_{12} \ldots P_{1n_{APB}} \\ P_{21} & \\ \cdot & \\ \cdot & \\ \cdot & \\ P_{n_{PDS}}1 & \ldots P_{n_{PDS}}n_{APB} \end{bmatrix} \quad \times \quad \begin{bmatrix} P_{11} & P_{12} \ldots P_{1n_{STG}} \\ P_{21} & \\ \cdot & \\ \cdot & \\ \cdot & \\ P_{n_{APB}}1 & \ldots P_{n_{APB}}n_{STG} \end{bmatrix} \quad \times \quad \begin{bmatrix} C_{11} & C_{12} \ldots C_{1n_c} \\ C_{21} & \\ \cdot & \\ \cdot & \\ \cdot & \\ C_{n_{STG}}1 & \ldots P_{n_{STG}}n_c \end{bmatrix} \quad = [RISK_1 \ldots RISK_{n_c}]$$

Figure 4-3   Equation 4.9 expanded to show the matrices and
the individual observations in the sample explicitly.
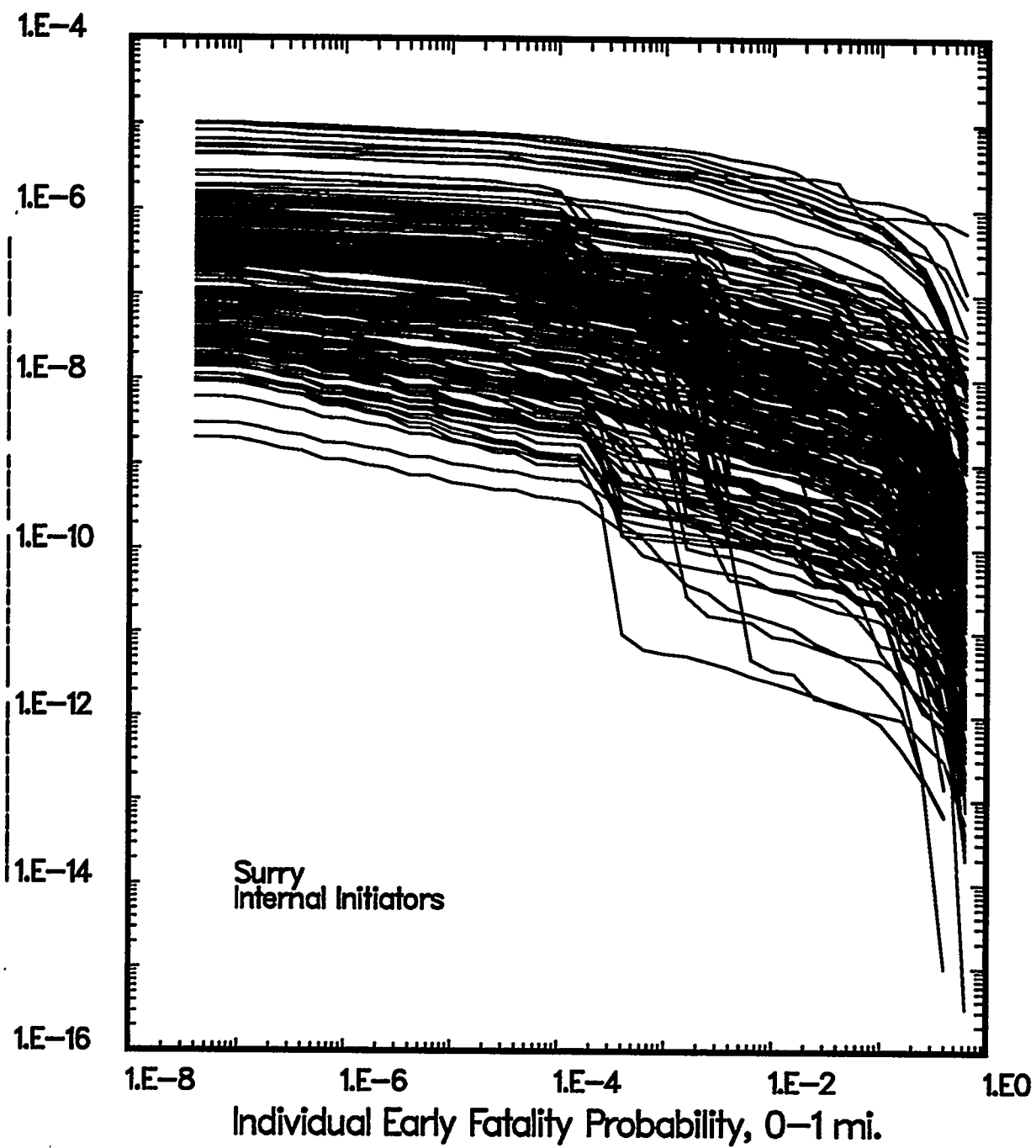
Figure 4-4   Example of family of exceedance frequency curves.

results of the analysis since both its occurrence and non-occurrence are incorporated into exceedance frequency curves of the form shown in Figure 4-2. The result of this type of uncertainty appears in the NUREG-1150 analyses in various forms: (1) initiating events do not always occur but rather have frequencies of occurrence, (2) a single initiating event may lead to more than one plant damage state in the accident frequency analysis, (3) a single plant damage state may lead to many accident progression bins in the accident progression analysis, and (4) many consequence estimates are obtained for each source term group in the consequence analysis due to the possible weather conditions that could exist at the time of an accident. Even if the information needed for the characterization of this type uncertainty and also for the estimation of source terms were perfectly known, the basic result of the analysis would still be exceedance frequency curves of the form shown in Figure 4-2.

The second type of uncertainty involves events or phenomena which are not believed to be stochastic, but about which little is known. An event is believed to always progress in one of several possible ways; due to our lack of understanding, which way is not known with certainty. For these variables and parameters that were believed to be non-stochastic, the analysis was structured to utilize a single value for each observation. As an example consider the failure pressure of a reactor containment. As a specific containment is involved, it can have only one failure pressure. As it cannot be tested to failure, there is uncertainty as to that failure pressure. For a variable such as this, it was considered appropriate that each observation in the sample had a single, specific failure pressure. Thus, from the aggregate distribution for failure pressure provided by the structural experts, a single value was chosen for each observation.

In practice, the division into stochastic and non-stochastic variables was not as clear as it is in the illustrative examples. Experts often disagreed as to the nature of a particular event. The grouping required to keep the problem tractable meant that cases had to be defined that included ranges for the initial and boundary conditions. In these situations, even for phenomena which are relatively well understood, it was natural that experts could not give precise results for most of the issues on which they were consulted. Insofar as possible, those events and phenomena which appeared to be stochastic in nature were treated probabilistically in each observation; those events and phenomena which appeared to be non-stochastic had a single, fixed value for each observation.

When the distributions were sampled and propagated through the analysis, results of the form shown in Figures 4-4 and 4-5 were generated. Each exceedance frequency curve in Figure 4-4 and each point on the annual risk curve in Figure 4-5 resulted from a combination of inputs (i.e., one sample element) that the expert review process deemed to be possible. The location of an individual estimate within the distributions in Figures 4-4 and 4-5 provides an indication of its likelihood given the variable distributions developed in the expert review process. (Technically, the probability of each sample element is zero; what the analysis actually yields are estimates of the subjective probability that the value of a risk result falls in specified intervals.) Additional discussion of

4.14
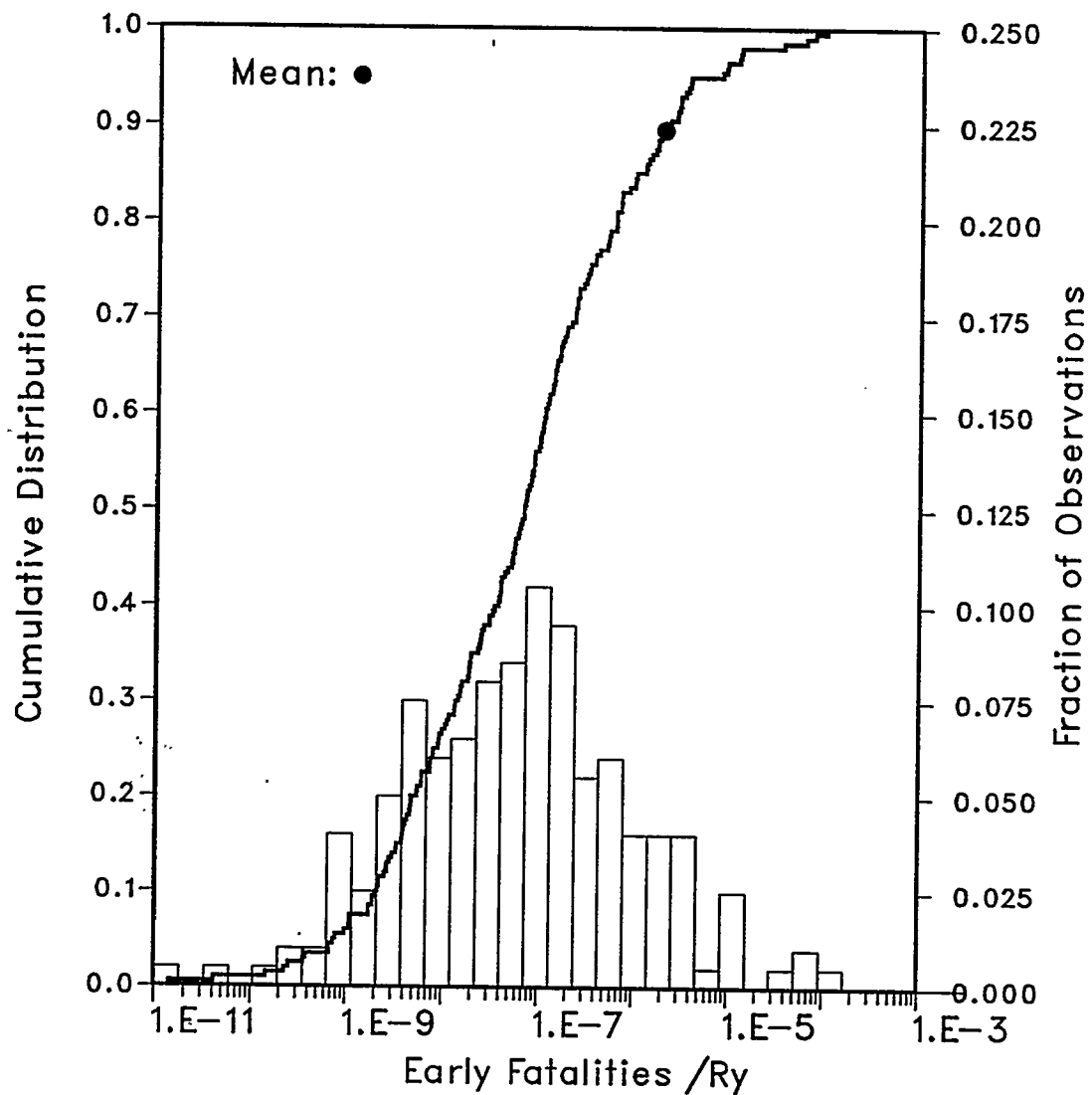
Figure 4-5 Representation of risk results as an estimate of a
probability density function (right axis) and as an estimate of
a cumulative distribution function (left axis).

the procedure used to select variables and assign distributions for use in the propagation of uncertainties is given in Chapter 9.

4.6   Calculation of Risk

The constituent parts of the risk calculation have been described in previous sections. As illustrated in Figure 4-1, a number of computer codes were used to generate a variety of intermediate information.   This information is then processed by an additional code to calculate risk. Two codes were used for this purpose: PRAMIS and RISQUE.   Both are essentially matrix manipulation codes. PRAMIS is described in a separate volume[24] and a listing of RISQUE is provided in Appendix B to this volume. As explained in this chapter and illustrated in Figure 4-3, the complete risk analysis can be represented in a matrix format.

The accident frequency analysis determines the vector f(IE) of initiating event frequencies and the vector f(PDS) of plant damage state frequencies. They are related by the n_{IE} by n_{PDS} matrix [P(IE→PDS)] as shown in (Eq. 4.1). $P(IE_i \rightarrow PDS_j)$ is the conditional probability that initiating event i will result in plant damage state j. Most plants had between ten and fifteen initiating events and about 25 PDSs. The PDSs were usually condensed into about ten groups for the accident progression analysis.

The output of the accident progression analysis is the vector f(APB) of accident progression bin frequencies. It is obtained by multiplying the vector f(APB) by the n_{PDS} by n_{APB} matrix [P(PDS→APB)] as shown in (Eq. 4.2). $P(PDS_j \rightarrow APB_k)$ represents the conditional probability that an accident grouped in plant damage state j will result in an accident grouped in accident progression bin k. For this study, there are between a few hundred and a few thousand accident progression bins depending on the plant.

The outcome of the source term analysis is a vector f(STG) of frequencies for the source term groups. It is obtained from f(APB) by use of the n_{APB} by n_{STG} matrix [P(APB→STG)] as shown in (Eq. 4.3). $P(APB_k \rightarrow STG_l)$ represents the conditional probability that the source term computed for accident progression bin k will be assigned to source term group 1 in the partitioning process. Each plant had approximately 50 source term groups.

The product of the consequence analysis is a matrix cSTG representing the consequences for each source term group. It is used to produce the risk vector as shown in (Eq. 4.4).   For this study, eight consequence measures were calculated, so the risk vector rC has eight components. The vector rC represents the consequences averaged over the weather. When all the constituent analyses are considered together, a matrix equation for risk is obtained, as shown in (Eq. 4.5)

Section 4.5 describes how sampling is used to produce estimates of uncertainty in risk. When the subscript s is used to denote the sample member, (Eq. 4.9) results. Each sample element is a complete evaluation for risk using a unique set of values for the sampled parameters and is equally likely.   Since consequence modeling uncertainty was not included in uncertainty analysis, only one consequence matrix C is required; i.e., the last term in Figure 4-3 is the same for every sample element.

The matrix manipulations described above are carried out by PRAMIS and RISQUE. The risk calculation is a fairly straightforward process, but the matrices involved are fairly large and must be performed for each element in the sample. The number of elements in the sample is 200 for Surry, Sequoyah, and Peach Bottom, 250 for Grand Gulf, and 150 for Zion. The results of the multiple evaluation for risk produce distributions for each risk measure. These distributions give an estimate of the uncertainty involved in the risk calculation. Insights about the analysis may be gained by statistical manipulation of the results. Descriptive statistics such as mean, median, variance, and 5th-percentile to 95th-percentile range can be calculated. The relative importance of the issues to uncertainty in risk can be determined through statistical techniques such as regression analysis. The individual observations can also be examined. For example, if the final distribution contains some results that are quite different from the others, the sample elements that produced these results can be identified and examined in detail to determine the causes of the outlying risk estimates.

One of the key developments in this program is the automation of the risk calculation and assembly process. This automation provides an efficient means of evaluating each constituent analysis and allows easy recalculation of risk to reflect changes in one of the constituent analyses. The automation of the computational process allows events and processes of particular interest to be examined by means of sensitivity studies.

While an estimate of risk and the uncertainty in risk is the overall objective, the intermediate results are also quite important. Each of the analysis steps resulted in the intermediate outputs discussed above. These results provided insights into the important phenomena in each stage of the accident progression. The intermediate results also provided checkpoints for consistency and understanding. Similar intermediate results are presented and discussed for each plant studied in this project.

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5.0 INTERFACE OF ACCIDENT SEQUENCE FREQUENCY ANALYSIS WITH THE ACCIDENT PROGRESSION ANALYSIS

5.1 Introduction

The Accident Frequency Analyses[1-4] conducted for the Surry, Peach Bottom, Sequoyah and Grand Gulf plants were state of the art Level I PRAs. The accident frequency analysis conducted for Zion[5] involved updating a previously conducted PRA for Zion[6-8] and was not as detailed as those conducted for the other four NUREG-1150 plants. A detailed presentation of the methods employed in the accident frequency analyses for Surry, Peach Bottom, Sequoyah, and Grand Gulf may be found in Volume I of the NUREG/CR-4550.[9] The methods utilized in the external events analyses for Surry and Peach Bottom are given in a separate document.[10] The methods employed for the Zion accident frequency analysis are described in the same volume of NUREG/CR-4550 that presents the results of the analysis.[5] The discussion of the accident frequency analyses in this section focuses on their integration into the complete risk analyses.

5.2 Initiating Events

The accident frequency analysis begins with the determination of events that could initiate a core damage accident and the frequencies with which these events are likely to occur. The NUREG-1150 analyses include two types of initiating events: internal events and external events. The distinction between internal events and external events is to some extent historical and not entirely consistent. Internal events are mostly initiating events that occur within the plant, such as transients, loss of coolant accidents (LOCAs), and steam generator tube ruptures, but also include losses of offsite power. External events are largely initiators that occur outside the plant, such as earthquakes, hurricanes, and floods, but also include fires within the plant.

The description of the initiating events

$$IE_1, IE_2, \ldots, IE_{nIE} \qquad \text{(Eq. 5.1)}$$

and the corresponding initiating event frequencies define the vector fIE that appears in (Eq. 4.1). For the NUREG-1150 analyses, potential accident initiating events, including external events for two plants, were examined and grouped according to the plant systems required to respond. Thus each initiating event is not really a single event but rather a large set of events that all place similar demands on the safety systems of a nuclear power plant. Similarly, the frequency fIE_i of initiating event IE_i is actually the sum of the frequencies of all events that are assigned to IE_i. As an example, Table 5-1 lists the internal initiating events that were used in the Surry analysis and their estimated mean frequencies.

Since the initiating event frequencies were considered to be uncertain, values for these frequencies were sampled from distributions, as described in Section 4.5. The result is a different vector fIE_s of initiating event frequencies for each sample element X_s as shown in (Eq. 4.9). In generating fIE_s, only the

5.1

frequencies of the initiating events indicated in (Eq. 5.1) change, the initiating events themselves do not change.

Table 5-1
Initiating Event Categories Used in the Surry PRA
This table is reproduced from Table 4.3-1 of Reference 1.

Abbreviation	Description	Mean Frequency (1/yr)
T_1	Loss of Offsite Power	7.7E-2
T_2	Transient with Loss of MFW	9.4E-1
T_3	Transient with MFW Initially Available	7.3
T_{5A}	Non-Recoverable Loss of DC Bus A	5.0E-3
T_{5B}	Non-Recoverable Loss of DC Bus B	5.0E-3
T_7	Steam Generator Tube Rupture	1.0E-2
A	Large Pipe Break (6" < D < 29")	5.0E-4
S_1	Medium Pipe Break (2" < D < 6")	1.0E-3
S_2	Small Pipe Break (0.5" < D < 2")	1.0E-3
S_3	Very Small Pipe Break (D < 0.5")	1.3E-2
V	Interfacing System Pipe Break	1.6E-6

5.3   Accident Sequence Analysis

The Accident Sequence Analysis consists of a number of important steps: development of systemic event trees that describe the nature of the accident in terms of plant safety systems, development of fault trees that determine the component failures required to fail each individual safety system, synthesis of the event and fault trees to obtain the sets of component failures that can lead from initiating events to core damage, and evaluation of the entire logic structure to determine the frequencies of accident sequences.

Systemic event trees were developed to reflect the interdependence between the successes and failures of the various safety systems in determining whether an initiating event resulted in core damage. These event trees were constructed using traditionally defined top events, such as the occurrence of containment venting, operation of high pressure injection system, etc. A list of top events (event tree headings or questions) is given in Table 5-2. Usually, a different event tree was constructed for each initiating event. Figure 5-1 shows a systemic event tree for the T_{1S} initiating event, Station Blackout at Surry Unit 1. The system failures in the event trees define the accident sequences, and are indicated by the lower branch for each top event. For the tree shown in Figure 5-1, there are 25 possible outcomes, or accident sequences. Since the top events are very general events, representing system successes and/or failures that could occur in a large number of ways, the accident sequences really describe groupings of similar accidents.

Fault trees were used to model the safety systems. The fault trees are quite detailed; for example, the Appendix to the Surry volume of NUREG/CR-4550[1] contains more than 100 pages of fault tree diagrams. The fault trees and the

SBO AT Unit 1	NRAC- HALF HOUR	RCI	SGI	AFW	NRAC- ONE HOUR	SEAL COOL FM U2	OPER. DEPRES	RCP SEAL LOCA	NRAC- SEAL LOCA	NRAC- SEVEN HOURS	No.	OUTCOME	DESCRIPTION
T1S	-	Q-	QS-	L	NR1	W2-	O-	SL-	NRS	NR7			
											1	CORE OK	T1S
											2	CORE OK	T1S-
											3	CORE MELT	T1S-NR7
											4	CORE OK	T1S-W2-
											5	CORE MELT	T1S-W2-NR7
											6	CORE OK	T1S-W2-SL-
											7	CORE MELT	T1S-W2-SL-NRS
											8	CORE OK	T1S-W2-O-
											9	CORE MELT	T1S-W2-O-NR7
											10	CORE OK	T1S-W2-O-SL-
											11	CORE MELT	T1S-W2-O-SL-NRS
											12	CORE MELT	T1S-L
											13	CORE OK	T1S-QS-
											14	CORE MELT	T1S-QS-NR7
											15	CORE OK	T1S-QS-W2-
											16	CORE MELT	T1S-QS-W2-NR7
											17	CORE OK	T1S-QS-W2-SL-
											18	CORE MELT	T1S-QS-W2-SL-NRS
											19	CORE MELT	T1S-QS-L
											20	CORE OK	T1S-Q-
											21	CORE MELT	T1S-Q-NR1
											22	CORE MELT	T1S-Q-L
											23	CORE OK	T1S-Q-QS-
											24	CORE MELT	T1S-Q-QS-NR1
											25	CORE MELT	T1S-Q-QS-L

Figure 5-1 Systemic Event tree for T1S-Station blackout at Surry Unit 1.
(This figure is reproduced from Figure 4.4-2 of Reference 1.)

5.3

event trees constitute a logic model of the plant which can be evaluated to produce combinations of events, including pre-existing faults, hardware failures, human actions, and recovery failures, that lead to core damage. These combinations of events are called "cut sets." A cut set is "minimal" if core damage does not occur if any event in the cut set is deleted. Cut sets which are not minimal are not of interest since the same accident is also represented by a minimal cut set. The SETS program[11] was used to solve the plant logic model and to determine the set of minimal cut sets. Cut sets are grouped into accident sequences. SETS can also be used to calculate the frequency of the accident sequences. Before this can be done, frequencies must be determined for all the initiating events, and probabilities found for all the component failures and human actions. This is termed quantification of the model. The frequencies and probabilities are based on experimental data, records of past occurrences, and modeling results.

Using the matrix notation introduced in Chapter 4, the results of the accident frequency analysis can be represented as

$$fAS = fIE \, P(IE \rightarrow MCS) \, P(MCS \rightarrow AS) = fIE \, P(IE \rightarrow AS) \, , \qquad \text{(Eq. 5.2)}$$

where fIE is the vector of frequencies for the initiating events, fAS is the vector of frequencies for the accident sequences, $P(IE \rightarrow MCS)$ is the matrix of transition probabilities from initiating events to minimal cut sets and $P(MCS \rightarrow AS)$ is the matrix that maps minimal cut sets to accident sequences.

Specifically,

$$fAS = [fAS_1, \ldots, fAS_{nAS}],$$

fAS_r = frequency per year for accident sequence r,

nAS = number of accident sequences,

$$P(IE \rightarrow AS) = \begin{bmatrix} pAS_{11} & \cdots & pAS_{1,nAS} \\ \vdots & & \\ pAS_{nIE,1} & \cdots & pAS_{nIE,nAS} \end{bmatrix}$$

pAS_{ir} = probability that initiating event i will lead to accident sequence r,

and the other symbols have been defined previously. The elements pAS_{ir} of $P(IE \rightarrow AS)$ are conditional probabilities: given that initiating event i has occurred, pAS_{ir} is the probability that accident sequence r will also occur.

The results of the accident sequence analysis are listings of minimal cut sets which can be used to calculate the elements of the transition matrix $P(IE \rightarrow MCS)$. In conjunction with the sample shown in (Eq. 4.8) it was necessary to evaluate

Table 5-2
Systemic Event Tree Headings used in the Surry PRA
This table is reproduced from Table 4.4-1 of Reference 1.

Abbr.	Heading	Description of Event
A	LARGE LOCA	Initiating Event (IE) -- large LOCA (6" to 29")
CS	CONT SYS	Top level event for containment heat removal includes CSS, ISR, and OSR system functions
CV	CORE VULNR TO CD	Probability of core damage for core vulnerable states (the core is being cooled but containment cooling has failed)
D1	HPI	Failure of charging pump system in high pressure injection mode
D2	HPI	Failure of charging pump system in feed and bleed
D3	SEAL COOL	Failure of charging pump system in seal injection flow mode
D4	HPI	Failure of charging pump system in emergency boration mode
D5	ACC	Failure of accumulators in injection mode
D6	LPI	Failure of low pressure safety injection system in injection mode
H1	LPR	Failure of low pressure safety injection system in recirculation mode
H2	HPR	Failure of charging pump system in high pressure recirculation mode
K	RPS	Failure of reactor protection system
L	AFW	Failure of auxiliary feedwater system for transients with reactor trip
L2	AFW	Failure of auxiliary feedwater system for ATWS

5.5

Table 5-2
Systemic Event Tree Headings
(continued)

Abbr.	Heading	Description of Event
L3	AFW	Auxiliary feedwater: failure of 1/3 AFW pumps to 1/2 SGs in SGTR
M	MFW	Failure of main feedwater
NR1	NRAC ONE HR.	Fail to recover offsite power within 1 hour
NR7	NRAC SEVEN HOURS	Fail to recover offsite power within 7 hours
O	OPER DEPRES	Operator fails to depressurize RCS during station blackout
OD	OPER DEPRES	Operator fails to depressurize RCS during small break initiators and steam generator tube rupture
P	PRV	Failure of both PORVs to open for feed and bleed
P1	PRV	Failure of one PORV to open for S_2L sequences
P2	PRV	RCS pressure relief fails in response to ATWS
PL	PWR LEVEL	Power level less than 25% of rated power
Q	RCI	Failure of pressurizer SRV/PORV to close after transient
QC	RCI	Failure of PORV to reclose after very small LOCA (SI causes relief valve to open)
QS	SGI	Loss of steam generator integrity via a relief valve, AFW steam line, decay heat removal line, or blowdown line
R	MAN SCRAM	Failure to effect manual reactor trip
S1	MEDIUM LOCA	IE -- medium LOCA (2" - 6")
S2	SMALL LOCA	IE -- small LOCA (1/2" to 2")

5.6

Table 5-2
Systemic Event Tree Headings
(continued)

Abbr.	Heading	Description of Event
S3	VERY SMALL LOCA	IE -- very small LOCA (less than 1/2")
SL	RCP SEAL LOCA	RCP seal leakage, greater than 2 lb/sec/pump
T	TBT	Turbine trip subsequent to ATWS
T1	LOSP	IE -- loss of offsite power
T1S	SBO	Station blackout
T2	LOSS OF MFW	IE -- loss of main feedwater
T3	TURB TRIP W/MFW	IE -- turbine trip with MFW available
T5	LOSS OF DC BUS	IE -- loss of DC bus
T7	SGTR	IE -- steam generator tube rupture
TK	ATWS	Anticipated transient without reactor scram
W	CCW	Failure of component cooling water to thermal barriers of all reactor cooling system pumps
W2	SEAL COOL FM U2	Failure to cool RCS pump seals from Unit 2 CCW
W3	RHR	Residual heat removal in shutdown cooling mode
Z	MTC UNF	Presence of "unfavorable" moderator temperature coefficient -- critical value greater than -7 pcm/°F
Z1	MTC LOW	Presence of very low moderator temperature coefficient -- critical value less than -20 pcm/°F

the matrix P(IE→MCS) for each sample element X_s. In contrast, the matrix P(MCS→AS) does not depend on the sampled variables and thus was fixed for all sample elements. The TEMAC program[12] used the minimal cut sets to evaluate P(IE→MCS) for each sample element X_s. Then the product of P_s(IE→MCS) and P(MCS→AS) provided a value for the nIE by nAS matrix P_s(IE→AS) for each sample element.

5.4   Plant Damage States

The information needed from the accident frequency analysis to determine the initial and boundary conditions for the accident progression analysis is termed the "plant damage state" (PDS). The PDS defines the plant condition at the onset of core damage, the point where the accident frequency analysis ends and the accident progression analysis begins. Each plant damage state (PDS) is a group of accidents that provide a similar set of initial and boundary conditions for the subsequent accident progression analysis. Thus, plant damage states form the interface between the accident sequence frequency analysis and the accident progression analysis. The development of the characteristics that define the plant damage states is based on an understanding of the important attributes of the accident progression and containment response analysis. These characteristics form the basis for the vector definition of the plant damage states

$$cPDS = [cPDS_1, cPDS_2, \ldots, cPDS_{ncPDS}] , \qquad \text{(Eq. 5.3)}$$

where $cPDS_r$, r=1,...,ncPDS, can be a numerical value or an alphanumeric descriptor for the status of a plant system. As an example, Table 5-3 lists the PDS characteristics for Surry. For Surry, ncPDS is 7 and $cPDS_1$ can take on any of the eight alphanumeric descriptors ($T, A, S_1, S_2, S_3, G, H, V$) listed in Table 5-3 for PDS characteristic 1. While the set of PDS characteristics can define a large number of PDSs, in reality, only a few dozen PDSs are of interest. Many combinations of the characteristics are mutually exclusive and many possible PDSs have frequencies below the cutoff value (1.0E-7/R-yr for Surry).

For all the plants except Peach Bottom each accident sequence was assigned to a single PDS. These assignments are reflected in the transformation matrix P(AS→PDS), which forms the link between the accident sequence frequencies and the plant damage state frequencies:

$$fPDS = fIE\, P(IE→AS)\ P(AS→PDS) = fAS\, P(AS→PDS) . \qquad \text{(Eq. 5.4)}$$

For Peach Bottom, the accident sequences were defined so broadly that for some sequences it was necessary to assign some of the minimal cut sets in the sequence to one PDS and other cut sets to another PDS. This required the construction of "bridge trees." The bridge trees were similar in nature to the systems event

Table 5-3 Plant Damage State Characteristics for Surry
(from Table 2.2-1 of Reference 13)

1. Status of RCS at Onset of Core Damage
    T = no break (transient)
    A = large break in the RCS pressure boundary
    S_1 = medium break in the RCS pressure boundary
    S_2 = small break in the RCS pressure boundary
    S_3 = very small break in the RCS pressure boundary
    G = steam generator tube rupture (SGTR)
    H = SGTR with loss of secondary system integrity
    V = large break in an interfacing system
2. Status of ECCS
    B = operated in injection and now operating in recirculation
    I = operated in injection only
    R = not operating, but recoverable
    N = not operating, not recoverable
    L = LPIS available in both injection and recirculation modes
3. Containment Heat Removal
    Y = operating or operable if/when initiated
    R = not operating, but recoverable
    N = never operated, not recoverable
    S = sprays operable, but no CHR (no SW to HXs)
4. AC Power
    Y = available
    P = partially available
    R = not available, but recoverable
    N = not available, not recoverable
5. Contents of RWST
    Y = injected into containment
    R = not injected, but could be injected if power recovered
    N = not injected, cannot be injected in the future
    U = injected, but confined to upper compartment
6. Heat Removal from the Steam Generators
    X = at least one AFWS operating, SGs not depressurized
    Y = at least one AFWS operating, SGs depressurized
    S = S-AFWS failed at beginning, E-AFWS recoverable
    C = S-AFWS operated until battery depletion, E-AFWS recoverable,
        SGs not depressurized
    D = S-AFWS operated until battery depletion, E-AFWS recoverable,
        SGs depressurized
    N = no AFWS operating, no AFWS recoverable
7. Cooling for Reactor Coolant Pump Seals
    Y = operating
    R = not operating, but recoverable
    N = not operating, not recoverable

trees and contained the additional top events needed to define the initial conditions for the accident progression analysis in sufficient detail. The bridge trees served as extensions of the systems event trees and allowed the minimal cut sets within the accident sequences to be assigned to PDSs. In the matrix notation used above, the calculation of PDS frequencies for Peach Bottom can be written

$$fPDS = fIE\,P(IE{\rightarrow}MCS)\ P(MCS{\rightarrow}PDS) = fIE\,P(IE{\rightarrow}PDS)\,, \qquad (Eq.5.5)$$

where $P(MCS{\rightarrow}PDS)$ is a matrix of transition probabilities from minimal cut sets to plant damage states and all other variables are defined in conjunction with (Eq. 5.2).

In order to provide input to the accident progression analysis the $P_s(IE{\rightarrow}AS)$ were regrouped using $P(AS{\rightarrow}PDS)$ to provide numerical values for the s set of nIE by nPDS matrices $P_s(IE{\rightarrow}PDS)$. For Peach Bottom the numerical values calculated for $P_s(IE{\rightarrow}MCS)$ were grouped into plant damage states using the transformation matrix $P(MCS{\rightarrow}PDS)$.

5.5   Core Vulnerable Sequences

Core vulnerable sequences are accidents in which the containment response to an accident affects whether core damage will occur. These sequences, which occur only for Peach Bottom in the NUREG-1150 analyses, require additional interaction between the accident sequence analysis and the accident progression analysis. Typically, in these accidents the core cooling systems are operating but containment heat removal is unavailable. If containment heat removal is not recovered and the containment fails, there is the possibility that the containment failure could cause failure of the core cooling systems and thus result in core damage.

The accident frequency analysis alone cannot resolve the outcome of core vulnerable sequences. The probability of containment failure and the probability of equipment failure given containment failure are determined in the accident progression analysis. The accident progression event tree (APET) is used to investigate the effects of the loss of containment cooling and the results of the evaluation are passed back to the accident frequency analysis to determine the total core damage frequency. This feedback link was established through direct interactions between the accident frequency and accident progression analysts. The dependencies between the analyses were included explicitly in the logic of the APET.

5.6   Products of the Accident Frequency Analysis

As discussed in previous sections, the result of a risk analysis is a set of triples

$$R_s = \{\ (S_{si},\ f_{si},\ o_{si})\,,\ i=1,\ \ldots,\ nS_s)\} \qquad (Eq.5.6)$$

for each sample element.

5.10

A traditional choice for reporting the results of the accident sequence frequency analysis is for each of the S_{si} to be the set of accidents that originate from initiating event i and progress to core damage. Then the f_{si} in (Eq. 5.6) correspond to

$$f_{si} = fIE_{si} \sum_j pAS_{sij},$$

(Eq. 5.7)

where the sum over j includes only accident sequences for which core damage is imminent. The o_{si} is a vector of analysis outcomes associated with S_{si}. Each o_{si} might contain the conditional probabilities of the plant damage states given the occurrence of an accident in S_{si}. In a Level I PRA, the analysis stops with the estimation of core damage frequency and so the vector o_{si} may not be evaluated. As an example, Figure 5-2 shows the distribution of core damage frequency estimated for internally initiated accidents at Surry. The frequencies displayed in this figure are

$$f_s = \sum_i \sum_j fIE_{si} pAS_{sij}, \quad s=1, \dots nLHS,$$

(Eq. 5.8)

and can be viewed as arising from the risk representation in (Eq. 5.6).

Another representation of the results of the accident sequence frequency analysis can be based on the plant damage states. In this representation each of the S_{si} is the set of accidents that progress to an accident in plant damage state i and the o_{si} are the vector definitions of the plant damage states shown in (Eq. 5.3). Since the plant damage state definitions do not change with sample members the o_{si} can be represented as o_i. The f_{si} in (Eq. 5.6) correspond to

$$fPDS_{si} = \sum_j fIE_{sj} pPDS_{sji},$$

(Eq. 5.9)

which is a reproduction of (Eq. 4.1). This representation is based on the results of the accident frequency analysis that are passed forward to the accident progression analysis.

For summary representations of results and for ease of analysis in the accident progression analysis, the plant damage states were grouped into plant damage state groups, denoted by i'. Then the $f_{si'}$ correspond to

$$fPDS_{si'} = \sum_{i'} \sum_j fIE_{sj} pPDS_{sji'}.$$

(Eq. 5.10)
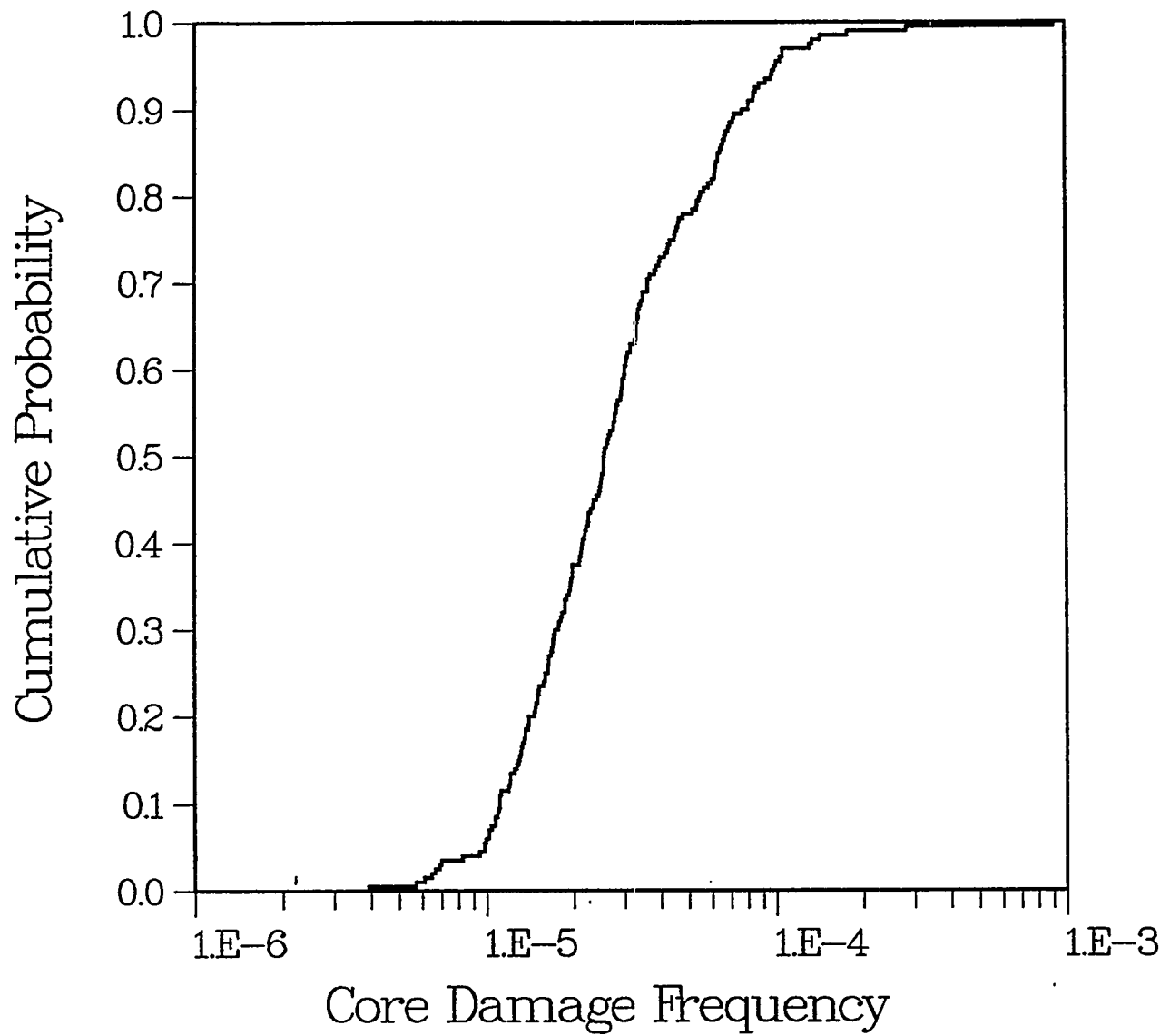
Figure 5-2   Cumulative distribution for core damage frequency for Surry.
(from Figure 5-1 of Reference 1)

Table 5-4 shows an example of this process using the accident frequency results for Surry. Column 1 lists the seven values of i'. In columns 2 and 3, are the PDS group labels and the mean frequencies of the distributions formed by the $f_{si'}$, respectively. Column 5 lists the 25 PDS, the o_i discussed above, which were found to be above the 1.0E-7/reactor-year cutoff frequency in the Surry accident frequency analysis and indicates in which PDS group each PDS is placed. Column 6 contains the mean values of the distributions formed by the f_{si}. Column 7 shows the percentage of the total mean core damage (TMCD) frequency contributed by each PDS.

Table 5-4
Plant Damage States and PDS groups for Internal Initiators at Surry
(from Table 2.2-2 of Reference 13)

Group Number	Group Name	Mean CD Freq (1) (1/R-yr)	Group % TMCD (2) Freq.	Plant Damage States	Mean CD Freq. (1) (1/R-yr)	% TMCD Freq.
1	Slow Blackout	2.2E-5	55.4	TRRR-RDY	1.0E-5	24.7
				S_3RRR-RDR	8.4E-6	20.7
				S_2RRR-RCR	2.0E-6	4.8
				TRRR-RDR	1.1E-6	2.7
				S_2RRR-RDR	7.0E-7	1.7
				S_3RRR-RCR	2.8E-7	0.7
2	LOCAs	6.1E-6	15.0	S_1IYY-YYN	1.7E-6	4.3
				S_1LYY-YYN	9.3E-7	2.3
				AIYY-YYN	8.5E-7	2.1
				ALYY-YYY	6.7E-7	1.6
				S_1NYY-YYN	6.1E-7	1.5
				S_3LYY-YYN	6.0E-7	1.5
				S_2LYY-YYN	4.5E-7	1.1
				ANYY-YYN	2.7E-7	0.7
3	Fast Blackout	5.4E-6	13.4	TRRR-RSR	5.4E-6	13.4
4	Event V	1.6E-6	4.1	V	1.6E-6	4.1
5	Transients	1.8E-6	4.3	TBYY-YNY	1.0E-6	2.6
				TLYY-YNY	7.1E-7	1.8
6	ATWS	1.4E-6	3.5	S_3NYY-YXN	7.5E-7	1.8
				TLYY-YXY	5.7E-7	1.4
				GLYY-YXY	9.0E-8	0.2
7	SGTR's	1.8E-6	4.4	HINY-NXY	1.4E-6	3.4
				GLYY-YXY	1.8E-7	0.4
				HINY-YXY	1.3E-7	0.3
				GLYY-YNY	1.0E-7	0.3
	Total	4.1E-5		Internal Initiators		

Notes: (1) Based on the sample of 200 observations used in the risk analysis.
(2) TMCD = total mean core damage.

Table 5-5 shows a slightly different set of information based on the representation of risk in (Eq. 5.10). In Table 5-5 the mean, median and the 5th and the 95th percentiles are shown for the distribution formed by the $f_{si'}$ for each i'.

Table 5-5
Summary of Core Damage Frequency Results for Surry.
This table is based on Table 3.2 in Reference 14.

PDS Group	Core Damage Frequency (1/R-yr)			
	5%	Median	Mean	95%
Internal Initiators	6.8E-6	2.3E-5	4.1E-5	1.3E-4
Short Term SBO	1.1E-7	1.7E-6	5.4E-6	2.3E-5
Long Term SBO	6.1E-7	8.2E-6	2.2E-5	9.5E-5
ATWS	3.2E-8	4.2E-7	1.6E-6	5.9E-6
Transient	7.2E-8	6.9E-7	2.1E-6	6.0E-6
LOCA	1.2E-6	3.8E-6	6.0E-6	1.6E-5
Interfacing System LOCA	3.8E-11	4.9E-8	1.6E-6	5.3E-6
SGTR	1.2E-7	7.4E-7	1.8E-6	6.0E-6
External Events				
Seismic (LLNL)	3.9E-7	1.5E-5	1.2E-4	4.4E-4
Seismic (EPRI)	3.0E-7	6.1E-6	2.5E-5	1.0E-4
Fire	2.2E-6	8.3E-6	1.1E-5	3.1E-5

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6.0   ACCIDENT PROGRESSION AND CONTAINMENT RESPONSE ANALYSIS

6.1   Introduction

The purpose of the accident progression and containment response analysis is to represent the physical progression of the accident from the point of imminent core damage until the completion of the release of radioactive material from the containment. The core degradation process is considered inside and outside of the reactor vessel. The events that accompany the failure of the reactor vessel are of particular interest since large containment loads are often generated at this time. This analysis determines the response of the containment to the stresses placed upon it at all times during the accident. This section presents only an overview of the accident progression and containment response analysis. More detail on the development and quantification of the accident progression model is contained in Appendix C of this volume and specific discussions for each plant are given in the plant volumes of this report.[1-5]

Many different accident progressions can follow the initial conditions defined by a PDS. Some of the phenomena involved are stochastic in nature, while others are not completely understood, so there is uncertainty in which way an accident will evolve. For each plant, a large, complex event tree is used to perform the accident progression and containment response analysis. The event tree, known as an accident progression event tree (APET), computes the probabilities for a large number of possible progressions. Each different progression is represented by a different path through the event tree. Information from similar paths is saved and passed to the source term analysis to define the initial and boundary conditions for the source term analysis.

The APETs formed a flexible logic structure that draws together and synthesizes the results of experiments, code analyses, and expert panels. They could also be relatively quickly evaluated by computer. Since the event trees developed for the NUREG-1150 accident progression analyses were quite large and had some novel features, a new computer code, EVNTRE,[6] was developed to evaluate these trees in a manner that was compatible with the Monte Carlo sampling approach to the determination of uncertainty.

The information base available for the accident progression analysis for NUREG-1150 consisted of the diverse results from more than 10 years of severe accident research within the reactor safety community. Basic knowledge of the phenomena involved in core degradation events was pursued by theoretical and experimental work. Building on the results of this research, mechanistic codes which synthesize the information available as a series of compatible computer models were developed. Detailed, mechanistic codes such as MELPROG[7] and CONTAIN[8] model parts of the core melt process from first principles insofar as possible. Integrated codes such as the Source Term Code Package (STCP),[9] MAAP[10] and, more recently, MELCOR[11] model the entire accident, but in less detail.

The results of these mechanistic codes, and the understanding of the accident phenomena that makes their development possible, form the starting point for the NUREG-1150 accident progression analyses. These codes have been very useful for learning how different phenomena interact, but they are not able to analyze a very wide range of accidents with diverse boundary conditions in a timely and

cost-efficient manner (see the discussion in Section 1 of Chapter 3). Further, these codes have not been fully validated against experiments. Thus, codes developed by different groups (for example, NRC and industry contractors) frequently include contradictory models and give different results for the same set of initial and boundary conditions. Finally, none of the codes available contained widely accepted models for all of the phenomena that may determine the progression of the accident or the amount of radioactivity released. Although many additional code analyses were conducted in the course of this study to answer specific questions or to provide information in areas where results were lacking, analysis results were available for only a small fraction of the many possible ways in which the accidents could develop. The supporting calculations performed for this study are listed in the second volume of this report.[12]

The accident progression analyses for NUREG-1150 attempted to utilize the results of all the mechanistic accident progression calculations that were available. This was accomplished by using expert panels to define distributions for the most important branch probabilities and parameters in the APETs. The experts reviewed the code results, considering the strong and weak points of each code, and provided distributions that accounted for the various modeling shortcomings.

6.2   Description of the Accident Progression Event Trees

The event trees used to perform the NUREG-1150 accident progression and containment response analyses consist of a series of questions about events that take place in the reactor vessel and the containment, and the physical phenomena affecting the progression of the accident. The development of the APET is the process of designing the logic structure that forms the tree. This involves determining the order of the questions, deciding what events and phenomena are to be included, setting up the dependencies between questions, and ensuring that all paths through the tree are consistent with physical reality.

The event tree divides the accident progression into several time periods, and considers the important events and phenomena in each period. Questions concern the availability of electric power and the containment heat removal systems, the pressure in the reactor cooling system, the state of the containment, and so on. The APETS that result are large and complex; it is not possible to depict them graphically. Multiple branches are allowed, and cases may be defined for each question that allow the branch probabilities to depend upon the branches taken at previous questions.

In addition, EVNTRE allows parameters to be defined and manipulated within the tree as it is being evaluated. Parameters are real FORTRAN variables that may be used to represent quantities such as the containment pressure or the mass of steam in the containment. The manipulation of parameters during evaluation of the APET is accomplished by FORTRAN subprograms denoted "user functions." The user function is compiled and linked with EVNTRE before the tree is evaluated. The user functions are evaluated at designated questions within the tree, and parameter values and the results of the user function calculations are used to determine the branch probabilities for these questions. For example, parameters might be used to represent the masses of different gases present in the containment, and the user function utilized to perform calculations with these parameters to determine if the containment atmosphere is flammable, and, if it

is, what the adiabatic pressure rise would be if the mixture were ignited. Through the use of parameters, basic principles such as mass conservation are incorporated into the event trees in order to ensure that each path through the tree is realistic.

The APETs developed to perform the NUREG-1150 accident progression and containment response analyses are powerful analysis tools. Although portions of a tree can be drawn out in typical event tree format, the complete tree exists only as the EVNTRE computer input file. A complete listing of this input file for each plant can be found in Appendix A of Volumes 3 to 7 of this report.[1-5] The event trees for Surry and Zion consisted of 71 questions; the event trees for the other three plants had over 100 questions. As an illustration of the types of questions included in the APETs, Table 6-1 lists the questions in the Surry APET. A table like this cannot show the branches for each question, describe the case structure that implements the dependency on the branches chosen at previous questions, indicate the number of parameters used, or discuss the user function evaluations, so it gives only an idea of the complexity and level of detail involved in these event trees.

The effect of uncertainties in phenomenological models is accounted for by including competing models, or the results of competing models in the tree. Which model or model result is to be used for each observation is selected by the stratified random sampling process in a manner similar to that used for sampling other quantities. The inclusion of different models or the results of different models adds to the complexity of the analysis since some paths through the event tree, which would be forbidden for a specific model, must be included when other models are considered. The complexity due to the inclusion of multiple phenomenological models is amplified by the need to consider a wider range of boundary conditions for the subsequent events.

Figure 6-1 schematically illustrates some aspects of the APETs used in this study by sketching one or two questions for several sections of an APET. The division of the questions in the tree into different sections or time periods is discussed in more detail in Appendix C of this volume and in Appendix A of Volumes 3 to 7 of this report.[1-5]

The questions in the first section of the tree determine the type of accident being modeled by setting the initial conditions. That is, the branch probabilities for the initial conditions follow directly from the specification of the PDS. Once the initial conditions are set, the progression of the accident is divided into three or more time periods. Typically, one or two groups of questions treat the period before failure of the vessel, another group of questions concerns the events at vessel breach, and one or more groups of

Table 6-1
Questions in the Surry APET
(Adapted from Table 2.3-1 in Reference 1)

1. Size & Location of RCS Break when the Core Uncovers?
2. Has the Reaction been brought Under Control?
3. For SGTR, are the Secondary System SRVs Stuck Open?
4. Status of ECCS?
5. RCS Depressurization by the Operators?

6. Status of Sprays?
7. Status of Fan Coolers?
8. Status of AC Power?
9. RWST Injected into Containment?
10. Heat Removal from the Steam Generators?

11. Did the Operators Depressurize the Secondary before the Core Uncovers?
12. Cooling for RCP Seals?
13. Initial Containment Condition?
14. Event V - Break Location under Water?
15. RCS Pressure at the Start of Core Degradation?

16. Do the PORVs Stick Open?
17. Temperature-Induced RCP Seal Failure?
18. Is the RCS depressurized before breach by opening the Pressurizer PORVs?
19. Temperature-Induced SGTR?
20. Temperature-Induced Hot Leg or Surge Line Break?

21. Is AC Power Available Early?
22. Rate of Blowdown to Containment?
23. Vessel Pressure just before Vessel Breach?
24. Is Core Damage Arrested?   No Vessel Breach?
25. Early Sprays?

26. Early Fan Coolers?
27. Early Containment Heat Removal?
28. Baseline Containment Pressure before Vessel Breach?
29. Time of Accumulator Discharge?
30. Fraction of Zr Oxidized In-Vessel during Core Degradation?

31. Amount of Zr Oxidized In-Vessel during Core Degradation?
32. Amount of Water in the Reactor Cavity at Vessel Breach?
33. Fraction of Core Released from the Vessel at Breach?

Table 6-1 (continued)

34. Amount of Core Released from the Vessel at Breach?
35. Does an Alpha Event Fail both Vessel & Containment?
36. Type of Vessel Breach?
37. Does the Vessel become a "Rocket" and Fail the Containment?
38. Size of Hole in Vessel (after ablation)?
39. Total Pressure Rise at VB? Large Hole Cases
40. Total Pressure Rise at VB? Small Hole Cases

41. Does a Significant Ex-Vessel Steam Explosion Occur?
42. Containment Failure Pressure?
43. Containment Failure and Type of Failure?
44. Sprays after Vessel Breach?
45. Is AC Power Available Late?

46. Late Sprays?
47. Late Fan Coolers?
48. Late Containment Heat Removal?
49. How Much Hydrogen Burns at Vessel Breach?
50. Does Late Ignition Occur?

51. Resulting Pressure In Containment?
52. Containment Failure and Type of Failure?
53. Amount of Core available for CCI?
54. Is the Debris Bed in a Coolable Configuration?
55. Does Prompt CCI Occur?

56. Is AC Power Available Very Late?
57. Very Late Sprays?
58. Very Late Fan Coolers?
59. Very Late Containment Heat Removal?
60. Does Delayed CCI Occur?

61. How much Hydrogen is produced during CCI?
62. Does Very Late Ignition Occur?
63. Resulting Pressure in Containment?
64. Containment Failure and Type of Failure?
65. Sprays after Very Late CF?

66. Fan Coolers after Very Late CF?
67. Containment Heat Removal after Very Late CF
68. Eventual Basemat Melt-through?
69. Eventual Overpressure Failure of Containment?
70. Basemat Melt-through before Overpressure Failure?
71. Final Containment Condition?

Boundary
Conditions:
Plant Damage
States

Recovery of
Core Prior to
Vessel Breach

In-Vessel
Processes and
Containment
Impact

Ex-Vessel
Processes and
Containment
Impact

Final
Outcome

Debris
Coolability

Late Containment
overpressure

Pressure
in vessel

Hydrogen
released?

Yes

Yes

Sytem
Setpoint

Recovery of
injection
Yes

No

No

High

No

No

High

Intermediate

Low

Hydrogen
Burn before
vessel breach

System
Setpoint

Yes

Pressure increase
due to H $_2$ burn during
CCI gas generation

High

No

Intermediate

Yes**

Low

No

* Amount of hydrogen released is sampled from continuous probability distribution
** Pressure increase is calculated from user function

Figure 6-1   Schematic representation of an accident progression event tree.

questions treats the period following vessel failure. A group of summary questions is often placed at the end of the tree. The limitations of a simple diagram like Figure 6-1 do not allow all periods to be shown. A diagram showing one path through the entire Surry APET may be found in Figure B.4 of Appendix B of NUREG-1150.[13]

Throughout the progression of a severe accident, operator intervention to recover systems has the potential to mitigate the accident's impact. Such human actions were considered in the APET analysis, using the same rules to quantify the outcomes as those used in the accident frequency analysis.

The general flow of the APETs should be evident by now, but the degree to which dependencies between questions can be treated may not be immediately apparent. In a question with case structure, the branch probabilities and parameter values depend on the branches taken in previous questions. That is, for most questions, the branch probabilities and parameter values are functions of the type of accident and the development of the accident to that point.

Development of the APET consists of selecting the questions to be asked in the tree, determining their order, and defining the case structure; that is, setting up the basic logical framework that forms the tree. Development of the tree also includes deciding what events and phenomena are to be included, determining what quantities are to be represented by parameters, and writing the user function. The dependency among questions is checked by carefully examining a large number of paths through the tree for consistency. The task of determining the values or distributions to be used for each branch probability and parameter is termed quantification and is summarized in the next section.

6.3   Quantification and Evaluation of the APETs

Quantification is the process of determining values or distributions for each branch probability and parameter in the APET. If a question is not to be sampled, fixed values for the branch probabilities and any parameters defined in that question will suffice. If the event or phenomenon treated by a question is important to risk or the uncertainty in risk, the question is sampled. For these questions, distributions must be determined for the branch probabilities and parameter values (if any). Although some quantification of the tree may be performed as it is developed, quantification is a distinct process from the building of the logic model.

In general, phenomenological models are not included in the event trees at each question. Rather, results of mechanistic code calculations enter the trees through distributions developed for branch probabilities and parameters. Numerous and diverse sources were utilized to determine the fixed values and distributions required before the tree could be evaluated. For questions such as those concerning the operability of equipment and availability of electrical power, probability distributions were derived from data analogous to and consistent with the process in the accident frequency analysis. The timing of key events for different types of accidents was estimated from a review of relevant code calculations and code calculations performed expressly for this study. For specific processes, results of code simulations and experiments were used.

6.7

The events or phenomena considered to be the most important to risk or the uncertainty in risk are termed "issues." The questions concerning these events and phenomena are sampled, and the distributions for the branch probabilities and parameters in these questions were determined by panels of outside experts. For questions concerning issues, the analyst's role is to ensure that the question in the tree accurately reflects the problem placed before the expert panel, form an aggregate distribution from the distributions provided by the individual experts, and see that the aggregate distribution is appropriately sampled. The second volume[12] of this report contains the distributions derived by the expert panels and explains how each expert arrived at his conclusions for every issue.

For quantities in the tree that were deemed less important to risk and the uncertainty in risk, but about which there is some uncertainty, the plant analyst constructed distributions based on experimental results, mechanistic code calculations, and informal discussions with experts at the national laboratories and elsewhere. The quantification of the tree is discussed, question by question, in Appendix A of each plant volume in this report.[1-5]

When the logic structure of the tree is complete and numerical values (single numbers or distributions) have been determined for each branch probability and parameter, the tree may be evaluated. This is performed by EVNTRE[6] and may be done in a single-evaluation mode or a multiple-evaluation mode. The single-evaluation mode is usually used during the development and quantification stages to check out the tree for each PDS or PDS group individually. EVNTRE utilizes the numbers in the tree input file for these evaluations and the evaluation is relatively straightforward. As explained in Section 3.3, the risk analyses for NUREG-1150 used an efficient stratified Monte Carlo technique[14] to determine the uncertainty in risk. This required on the order of 200 evaluations of the tree when it was evaluated in the "production" mode. EVNTRE was designed with a multiple evaluation feature specifically for this purpose. Whether evaluated with fixed values or in the sampling mode, evaluation of the tree results in a large number of paths through the tree with non-zero probabilities. The treatment of the numerous paths through the tree for each evaluation is the subject of the next section.

6.4   Grouping of Event Tree Outcomes

The number of paths through the APET can be very large. For an APET with N questions, each with only two outcomes, the number of paths is 2^N. Because of the multiple branches allowed in the APETs, the number of paths is more like 3^N or 4^N. To list and describe each consistent path individually for one of the NUREG-1150 APETs is not feasible. Therefore, during the evaluation of the APET, EVNTRE groups paths through the tree into categories referred to as accident progression bins (APBs). EVNTRE also calculates the sum of the conditional probabilities of the paths placed in each accident progression bin. A "rebinner" code, PSTEVNT,[15] allows the APBs to be manipulated and combined in any desired fashion after the evaluation of the APET is complete. The initial "binning" into APBs is designed to preserve all the information that is needed to define the initial and boundary conditions for the source term analysis and to supply enough detail to characterize the accident progression analysis. The rebinner is used to further group the initial bins into more general categories, for example, to illustrate the importance of a specific aspect of accident phenomenology.

The accident progression bins are groups of categories or characteristics used to define the accidents. These characteristics form the basis for the vector definition of the accident progression bins

$$[cAPB_1, cAPB_2, \ldots, cAPB_{ncAPB}] \qquad \text{(Eq. 6.1)}$$

where $cAPB_k$, k=1, ...,ncAPB, can be a numerical value or an alphanumeric descriptor for some aspect of the accident. As an example of a set of APB characteristics, Table 6-2 lists the 11 characteristics used in the binning for the Surry analysis. Letters are used to represent the values chosen for each characteristic in the binning. Since the Surry "binner" has 11 characteristics, each bin for Surry is defined by a string of 11 letters. Table 6-2 shows that the binning preserves information important to the source term analysis such as time and size of containment failure, and the operation of processes that remove radioactive material. The bins summarize the overall outcomes of the event tree evaluation, and do not include information about the branches taken at most of the individual questions in the tree.

There are two or more possible values, or attributes, for each binning characteristic. As an example, the last characteristic in the Surry binner is one of the more simple ones: the letter "A" is used to indicate that there is only one large hole in the RCS, and the letter "B" is used to indicate that there are two large holes in the RCS. Thus, Characteristic 11 has two attributes. Table 6-3 shows the attributes or possible values of the first two characteristics used for the initial binning for the Surry analysis. There are 8 attributes for the first characteristic and 9 for the second characteristic. An APB that had "ED" as its first two letters indicates an accident that had containment failure an hour or more after vessel breach with sprays operating throughout the accident.

6.9

Table 6-2.   Accident Progression Bin Characteristics for Surry
(from Section 2.4 of Reference 1)

Characteristic	Abbreviation	Description
1	CF-Time	Time of Containment Failure
2	Sprays	Periods in which Sprays Operate
3	CCI	Occurrence of Core-Concrete Interactions
4	RCS-Pres	RCS Pressure before Vessel Breach
5	VB-Mode	Mode of Vessel Breach
6	SGTR	Steam Generator Tube Rupture
7	Amt-CCI	Amount of Core Available for CCI
8	Zr-Ox	Fraction of Zr Oxidized In-Vessel
9	HPME	Fraction of the Core in HPME
10	CF-Size	Size or Type of Containment Failure
11	RCS-Hole	Number of Large Holes in the RCS after VB

Table 6-3. Attributes of the First Two Accident Progression Bin
Characteristics for Surry (from Section 2.4 of Reference 1)

Characteristic 1 - Containment Failure Time

A - V-Dry   Event V, Break Location not Submerged

B - V-Wet   Event V, Break Location Submerged

C - Early-CF   Containment Failure before Vessel Breach

D - CF-at-VB   Containment Failure at Vessel Breach

E - Late-CF   Late Containment Failure (during the initial part of CCI,
                     nominally a few hours after VB)

F - VLate-CF   Very Late Containment Failure (during the latter part of
                     CCI, nominally 8 to 12 hours after VB)

G - Final-CF   Containment Failure in the Final Period (nominally about
                     24 hours after VB)

H - No-CF   No Containment Failure

Characteristic 2 - Sprays

A - Sp-Early   The sprays operate only in the Early period.

B - Sp-E+I   The sprays operate only in the Early and Intermediate
                     periods.

C - Sp-E+I+L   The sprays operate only in the Early, Intermediate, and
                     Late periods.

D - SpAlways   The sprays always operate during the periods of interest
                     for fission product removal.

E - Sp-Late   The sprays operate only in the Late period.

F - Sp-L+VL   The sprays operate only in the Late and Very Late periods.

G - Sp-VL   The sprays operate only in the Very Late period.

H - Sp-Never   The sprays Never operate during the accident.

I - Sp-Final   The sprays operate only during the Final period, which is
                     not of interest for fission product removal.

6.11

6.5 Products of Accident Progression Analysis

As discussed Chapter 2, the results of a risk analysis can be represented by a set of triples R_s

$$R_s = \{ (S_{sk}, f_{sk}, o_{sk}), \; k=1, \ldots, nS_s \} , \qquad \text{(Eq. 6.2)}$$

where (Eq. 6.2) is (Eq. 2.4) rewritten with the dummy subscript changed to k and the dependency on the sample element, s, has been made explicit as discussed at the end of Section 3.3.

A possible choice for reporting the results of the accident progression analysis is for each of the S_{sk} to correspond to the set of accidents that have been grouped in accident progression bin k. Then, the f_{sk} are analogous to the $fAPB_k$ of (Eq. 4.2). The vector $o_{sk} = o_k$, for sample member element s, is the definition of accident progression bin k (the $cAPB_k$ of Eq. 6.1). The vector o_k is not independent of the sample member s because different APBs are selected for different sample elements. This representation of risk is analogous to the representation in (Eq. 5.9) for the results of the accident frequency analysis.

Figure 6-2 is an illustration of the use of this risk representation. However, for this figure accidents are grouped into more general categories than accident progression bins. These are called summary accident progression bins. For this figure, S_{sk} corresponds to the set of accidents that have been grouped into summary accident progression bin k. The frequencies f_{sk} are given by

$$f_{sk} = \sum_j fPDS_{sj} \, pAPB_{sjk} . \qquad \text{(Eq. 6.3)}$$

Finally, the $o_{sk} = o_k$ is a vector descriptor of the summary accident progression bin for group k. In Figure 6-2 the distribution of f_{sk} is shown for each k using a histogram. That is, the abscissa represents the possible values for the f_{sk} and the width of the cell forming part of the histogram is proportional to the number of times f_{sk} fell within the interval defined by the vertical boundaries of the cell.

The seven summary APB groups that form the o_k in Figure 6-2 are explained in Table 6-4. The order in which the summary APBs are listed in this table is important: there is a priority in assigning APBs to the summary groups since an APB may meet the criteria for more than one summary group. An APB is placed in the first summary group for which it satisfies the criteria. For example, failure of the containment by basemat melt-through (BMT) may follow a bypass accident. Since the bypass of containment is more important than the melt-through in determining the offsite consequences, this accident is placed in the Bypass summary group.
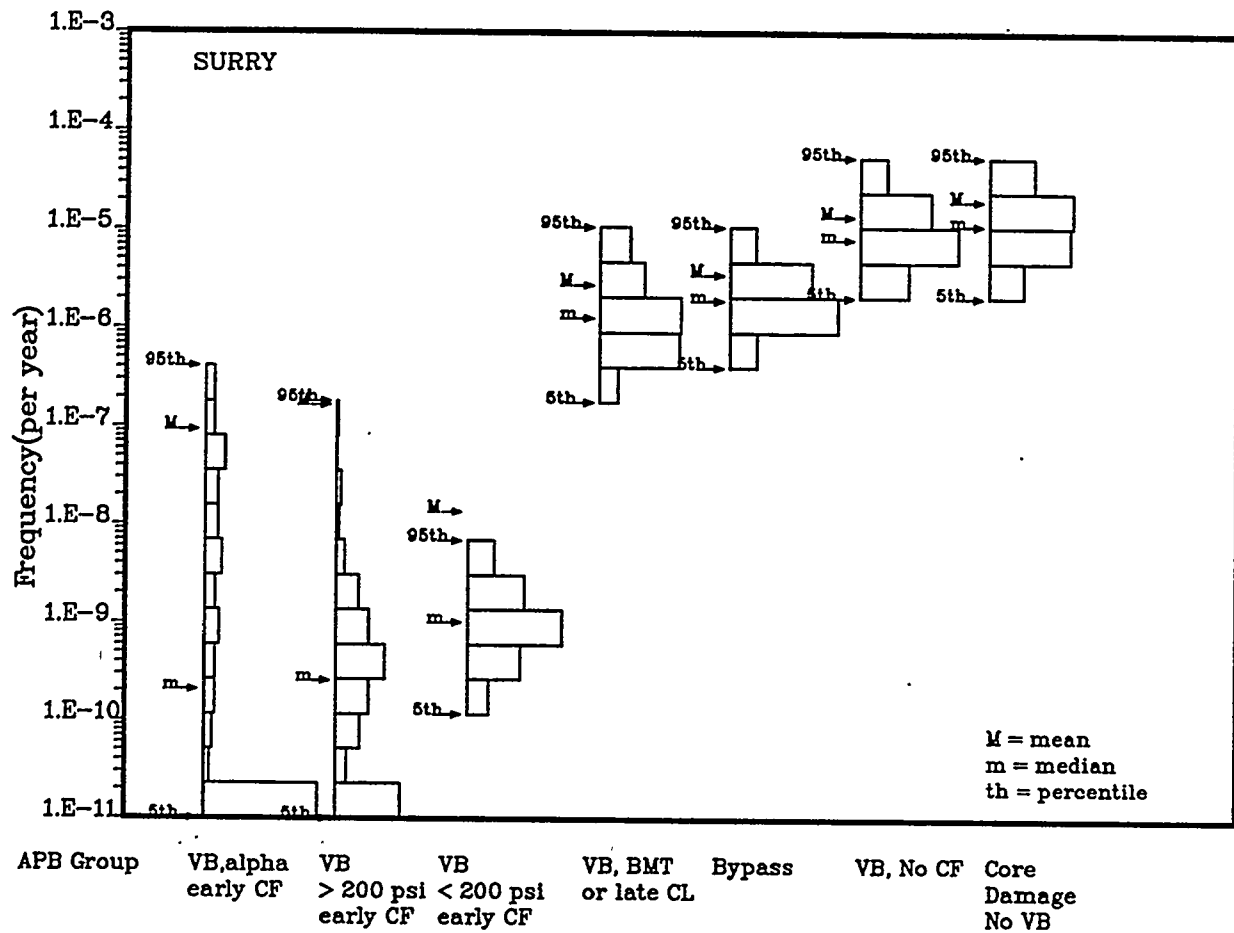
Figure 6-2 Distribution of frequencies of summary APB groups for Surry
(Figure 2.5.3 from Reference 1)

Table 6-4
Definition of the Seven Summary APB Groups for Surry
(Complete definition in Section 2.4.3, Reference 1.)

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1   Bypass - bypass of containment by an interfacing system LOCA (Event V) or an SGTR

2   VB, alpha, early CF - an energetic steam explosion in the reactor vessel fails both the vessel and the containment

3   No VB - the vessel remains intact, the containment does not fail and is not bypassed

4   VB > 200 psi, early CF - the RCS is above 200 psi when the vessel fails, the containment fails at vessel breach or shortly thereafter

5   VB < 200 psi, early CF - the RCS is below 200 psi when the vessel fails, the containment fails at vessel breach or shortly thereafter

6   VB, BMT or late CF - the containment fails many hours after vessel failure by the development of a leak or by basemat melt-through

7   VB, No CF - the vessel fails, but there is no failure or bypass of the containment

---

For many of the tables and figures produced in this study the components of the vector in (Eq. 4.2) are reported, rather than the vector $fAPB_{sk}$ itself. In particular, since the $fPDS_{sj}$ are reported as results of the accident frequency analysis, the $pAPB_{sjk}$, or groupings of them, are reported as the principal results of the accident progression analysis. The f_{sk} of (Eq. 6.2) are replaced by $pAPB_{sjk}$. S_{sjk} corresponds to the set of accidents that have been grouped in PDS group j and APB k. The $o_{sjk} = o_{jk}$ are constructed to include both the vector definition of PDS j and the vector definition of APB k. In this representation, as with those described for the accident frequency analysis, the number of results reported is reduced by grouping both the PDSs or PDS groups and the APBs.

The scheme used to generate Table 6-5 is based on the PDS groups defined in Section 5.6. For this scheme the $pAPB_{sjk}$ are defined by

$$pAPB_{sjk} = \sum_{j} fPDS_{sj}\, pAPB_{sjk} / \sum_{j} fPDS_{sj} \qquad \text{(Eq. 6.4)}$$

6.14

Table 6-5 Results of the Accident Progression Analysis for Surry
Internal Initiators - PDS Group 1 - Slow SBO (from Table 2.5-1 of Ref. 1)

Order	Bin	Prob.**	No.	CF Occur.	Sprays Time	CCI	RCS Pres.	VB Mode	Amt CCI	Zr Ox	HPME	CF Size
Five Most Probable Bins*												
1	HDCDFCDBDFB	0.171	121	No-CF	Always	No-CCI	LoPr	No-VB	No-CCI	Hi	No	No-CF
2	HDCDFCDADFB	0.145	113	No-CF	Always	No-CCI	LoPr	No-VB	No-CCI	Lo	No	No-CF
3	HDCDFCDADFA	0.046	41	No-CF	Always	No-CCI	LoPr	No-VB	No-CCI	Lo	No	No-CF
4	HDCCFCDBDFA	0.040	38	No-CF	Always	No-CCI	ImPr	No-VB	No-CCI	Hi	No	No-CF
5	HFADBCABDFA	0.038	33	No-CF	L+VL	PrmDry	LoPr	Pour	Large	Hi	No	No-CF
Five Most Probable Bins that have VB*												
5	HFADBCABDFA	0.038	33	No-CF	L+VL	PrmDry	LoPr	Pour	Large	Hi	No	No-CF
10	HFADBCAADFB	0.033	104	No-CF	L+VL	PrmDry	LoPr	Pour	Large	Lo	No	No-CF
14	HDCDBCDADFB	0.017	113	No-CF	Always	No-CCI	LoPr	Pour	No-CCI	Lo	No	No-CF
15	HDCDBCDBDFB	0.017	121	No-CF	Always	No-CCI	LoPr	Pour	No-CCI	Hi	No	No-CF
16	HGADBCABDFB	0.016	120	No-CF	VL	PrmDry	LoPr	Pour	Large	Hi	No	No-CF
Five Most Probable Bins that have VB and Early CF*												
64	DHADDCBADBB	0.0012	50	CFatVB	Never	PrmDry	LoPr	Alpha	Medium	Lo	No	Rupture
73	DHADDCBBDBB	0.0010	64	CFatVB	Never	PrmDry	LoPr	Alpha	Medium	Hi	No	Rupture
95	DFACACABACB	0.0007	1	CFatVB	L+VL	PrmDry	ImPr	HPME	Large	Hi	Hi	Leak
145	DFAAACAAABA	0.0004	4	CFatVB	L+VL	PrmDry	SSPr	HPME	Large	Lo	Hi	Rupture
172	DFADBCAADCB	0.0003	1	CFatVB	L+VL	PrmDry	LoPr	Pour	Large	Lo	No	Leak

* A listing of all bins, and a listing by observation are available on computer media.
** Mean probability conditional on the occurrence of the PDS.

6.15

Table 6-5 lists results for a single PDS group, i.e., j = 1. In Table 6-5 the vector definitions of the accident progression bins, the cAPB, for a number of important bins (column 2) and the mean values of the distribution formed from the $pAPB_{sjk}$ (column 3), where k corresponds to the bin described in column 1 are shown. The rest of the columns in Table 6-5 are the mnemonic descriptors for 9 of the 11 bin characteristics. The mnemonic descriptors for the first two bin characteristics are given in Table 6-3. No mnemonic descriptor appears for the sixth bin characteristic since no SGTRs occur among the most probable bins for this PDS group. The last characteristic, RCS-Hole, has also been omitted since it is of less interest than the others.

Another representation of accident progression analysis results based on (Eq. 6.4) is shown in Figure 6-3. The conditional probability of core damage arrest is defined as

$$pCDA_{sj} = \sum_{k \in S(CDA)} fPDS_{sj}\, pAPB_{sjk} \,/\, fPDS_{sj} \qquad\qquad \text{(Eq. 6.5)}$$

for each plant damage state group j, where the sum over k includes only accident sequences that resulted in core damage arrest and were included in plant damage state group j. The distributions formed by the $pCDA_{sj}$ are shown in histogram form for each j, along with the mean of the distribution and the 5th and the 95th percentile of the distribution.

Still another representation of accident progression analysis results based on (Eq. 6.4) is shown in Figure 6-4. This figure is similar to Figure 6-3. The conditional probability of early containment failure is defined as

$$pECF_{sj} = \sum_{k \in S(ECF)} fPDS_{sj}\, pAPB_{sjk} \,/\, fPDS_{sj} \qquad\qquad \text{(Eq. 6.6)}$$

for each plant damage state group j, where the sum over k includes only accident sequences that resulted in early containment failure and were included in the plant damage state group j.

Finally, an important representation of the accident progression results also based on (Eq. 6.4) is shown in Figure 6-5. Figure 6-5 shows the mean values of the distributions for the $pAPB_{sjk}$ for each j and k. Thus Figure 6-5 is a summary representation of the distribution formed by the nLHS $pAPB_{sjk}$ matrices, where nLHS is the number of latin hypercube samples. The matrices are the principal product of the accident progression analysis.
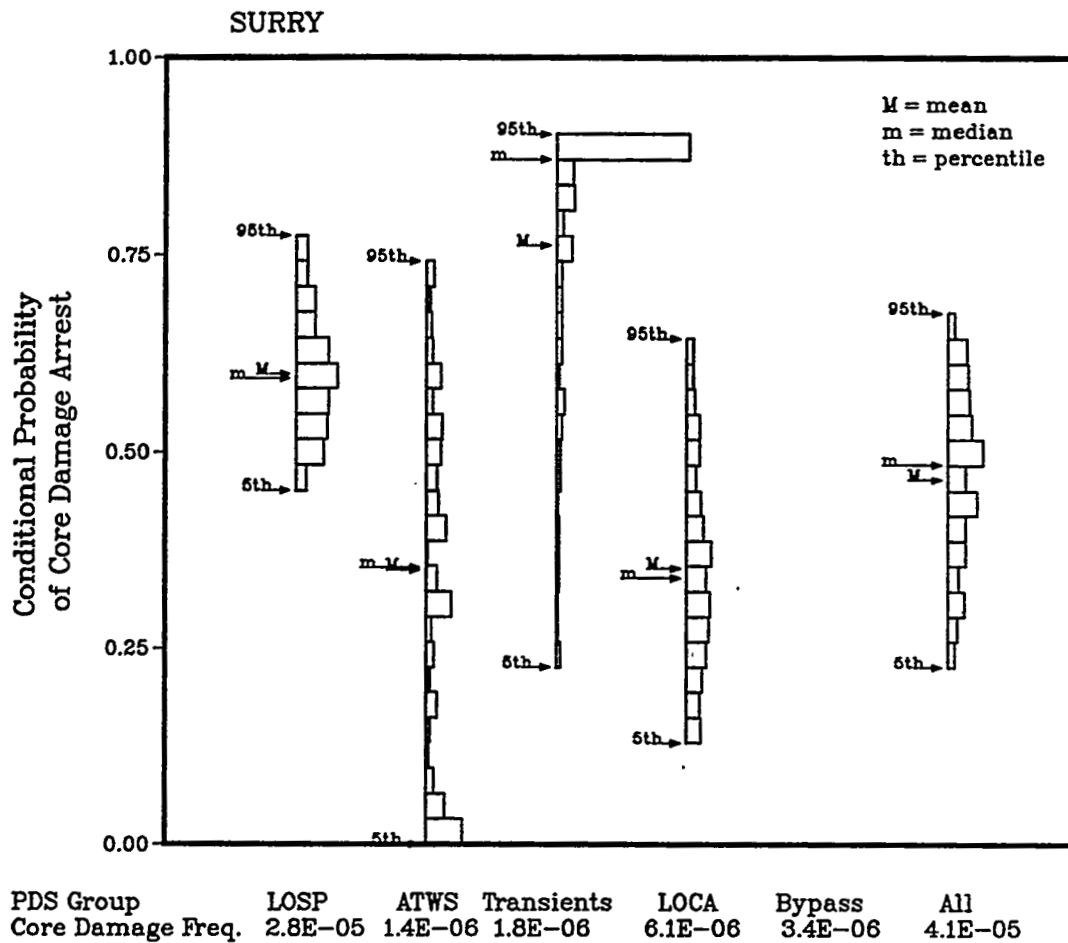
Figure 6-3 Conditional probability of core damage arrest for internal initiators at Surry (from Figure 2.5-1 of Reference 1)

6.17
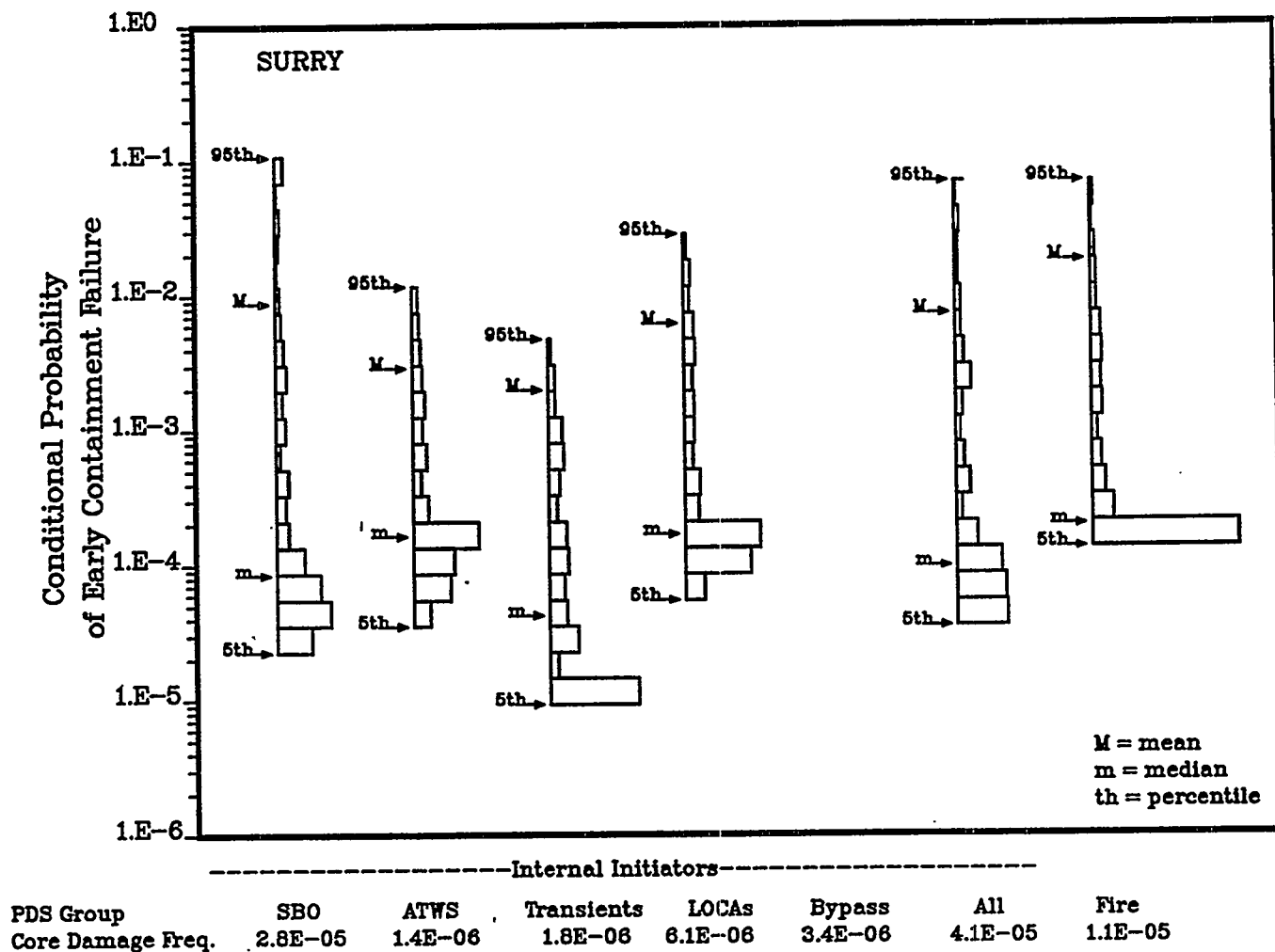
Figure 6-4 Conditional probability of early containment failure for internal and fire initiators at Surry (from Figure 2.5-2 of Reference 1).

SUMMARY ACCIDENT PROGRESSION BIN GROUP

SUMMARY PDS GROUP
(Mean Core Damage Frequency)

SUMMARY ACCIDENT PROGRESSION BIN GROUP	Internal Initiators						Fire
	LOSP (2.8E-05)	ATWS (1.4E-06)	Transients (1.8E-06)	LOCAs (6.1E-06)	Bypass (3.4E-06)	All (4.1E-05)	(1.1E-05)
VB, alpha, early CF	0.003	0.003		0.005		0.003	0.005
VB > 200 psi, early CF	0.005		0.001	0.001		0.004	0.013
VB, < 200 psi, early CF							
VB, BMT or late CL	0.079	0.046	0.013	0.055		0.059	0.292
Bypass	0.003	0.078	0.007		1.000	0.122	
VB, No CF	0.310	0.523	0.217	0.586		0.346	0.690
No VB	0.599	0.350	0.762	0.352		0.466	

Key: BMT = Basemat Melt-Through
CF = Containment Failure
CL = Containment Leak
VB = Vessel Breach

SURRY

Figure 6-5 Mean probability of the summary APBs for each summary PDS group for Surry - internal and fire initiators (from Figure 2.5-3 of Reference 1).

6.19

6.6 References

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7.0 SOURCE TERM ANALYSIS

7.1 Introduction

The results of the accident progression analysis consist of a large group of accident progression bins, with a conditional probability for each. The next step in the integrated risk analysis is the estimation of a source term for each accident progression bin. A source term is a characterization of the radionuclide release to the environment associated with an accident progression bin. In the NUREG-1150 PRAs, each source term contains the following information:

$$ST = [TW, T_1, DT_1, T_2, DT_2, ELEV,$$
$$E_1, (ST_{1_i} = i = 1, \ldots 9),$$
$$E_2, (ST_{2_i} = i = 1, \ldots 9)] \qquad \text{(Eq. 7.1)}$$

where

TW	=	time (sec) at which warning to the public is given (time 0 is taken to be scram time),
T_1	=	time (sec) at which the first release segment begins,
DT_1	=	length (sec) of the first release,
T_2	=	time (sec) at which the second release begins,
DT_2	=	length (sec) of second release,
ELEV	=	elevation (m) of release,
E_1	=	energy release rate (watts) during the first release,
$ST1_i$	=	release fraction for radionuclide class i, i = 1, ..., 9, in the first release,
E_2	=	energy release rate (watts) during the second release,
$ST2_i$	=	same as $ST1_i$ but for the second release.

The nine radionuclide classes are defined in Table 7-1. Two releases are defined to accommodate the releases that occur in the "classic" accident. In this accident, the containment fails before or at vessel breach and there is a large release to the environment when the vessel fails. This release is often termed the early release. The core is still in the vessel when the radionuclides in this release leave the core, so they pass to the reactor cooling system and this release is sometimes called the RCS release. In the "classic" accident, the second release occurs some hours later when the reaction of the core with the concrete of the basemat causes additional radioactive material to be released. This release is typically much longer and of lower concentration than the first release. It is often called the CCI or late release. In accidents that do not

7.1

fit this "classic" accident, the two releases are redefined as described below and in NUREG/CR-5360.[1]

Table 7-1
Isotopes in Each Radionuclide Release Class

Release Class	Isotopes Included
1. Inert Gases	Kr-85, Kr-85M, Kr-87, Kr-88, Xe-133, Xe-135
2. Iodine	I-131, I-132, I-133, I-134, I-135
3. Cesium	Rb-86, Cs-134, Cs-136, Cs-137
4. Tellurium	Sb-127, Sb-129, Te-127, Te-127M, Te-129,Te-129M, Te-131M, Te-132
5. Strontium	Sr-89, Sr-90, Sr-91, Sr-92
6. Ruthenium	Co-58, Co-60, Mo-99, Tc-99M, Ru-103, Ru-105, Ru-106, Rh-105
7. Lanthanum	Y-90, Y-91, Y-92, Y-93, Zr-95, Zr-97, Nb-95, La-140, La-141, La-142, Pr-143, Nd-147, Am-241, Cm-242, Cm-244
8. Cerium	Ce-141, Ce-143, Ce-144, Np-239, Pu-238, Pu-239, Pu-240, Pu-241
9. Barium	Ba-139, Ba-140

The purpose of this section is to provide an overview of the procedures used to estimate the quantities shown in (Eq. 7.1) for each individual accident progression bin. This is typically done in one of two ways. The first is to perform a small number of very detailed source term calculations and then to approximate the source term for every accident progression bin by the results of one of these calculations. In this manner, every source term comes from a mechanistic code calculation, but resolution is lost by the use of the same source term for a wide range of accident progression bins. The second possibility is to use mechanistic code calculations and other sources of information to develop the means to calculate a source term estimate for each accident progression. With this approach, each accident progression bin is not assigned a source term that was generated by a specific mechanistic calculation. Rather, available source term information and the specific properties of the accident progression bin are used to construct a source term. It is this second approach that is used in the PRAs performed for NUREG-1150.

Specifically, the approach to source term estimation used for the integrated NUREG-1150 PRAs was to construct for each plant a fast-running computer code based on a high-level description of the accident as represented by the characteristics of the accident progression bins. These codes, collectively referred to as the XSOR codes, are similar in approach and scope, but differ in detail in order to reflect the features unique to each plant. The codes are: SURSOR for Surry, SEQSOR for Sequoyah, ZISOR for Zion, PBSOR for Peach Bottom, and GGSOR for Grand Gulf. A listing of each code appears in Appendix B of the appropriate plant volume of this report.[2-6]

Information on timing and energy release rates for the XSOR codes was derived directly from mechanistic code calculations. The release fractions are determined by first decomposing the release fractions into their constituent factors or terms as explained below, where each factor represents a specific step or event in the release process. Then, an expert review process was used to assemble information on most of these factors. The factors deemed less important to risk were considered by the staff analysts and other NRC contractors in a less formal fashion. The XSOR codes may be viewed as implementing a mapping from the individual characteristics of accident progression bins to the distributions for each factor in (Eq. 7.1). The XSOR codes also assemble the resultant source term and implement the sampling procedure used to estimate the uncertainty.

7.2   Decomposition of Release Fractions

The incorporation of information obtained from mechanistic code calculations and experiments into the release fraction estimates used in NUREG-1150 is facilitated by a suitable decomposition. The decomposition used in NUREG-1150 involves two parts.

The first part of the decomposition is the division of the total release based on the time of release from the core and the pathway followed. Specifically, the following division is used:

$$rf_i = rf_{vi} + rf_{ei} + rf_{hi} + rf_{li} + rf_{si} , \hspace{2cm} \text{(Eq. 7.2)}$$

where

rf_i = total release fraction for radionuclide release class i,

rf_{vi} = release fraction for radionuclide release class i for releases that begin in the vessel (i.e., releases from fuel to the reactor cooling system atmosphere before the vessel fails),

rf_{ei} = release fraction for radionuclide release class i for releases that begin ex-vessel (i.e., release from fuel due to core-concrete interactions after vessel failure),

rf_{hi} = release fraction for radionuclide release class i for releases that arise from high-pressure melt ejection,

7.3

rf$_{li}$ =   release fraction for radionuclide release class i for late releases (e.g., revolatilization of material deposited in the vessel or in the containment),

and

rf$_{si}$ =   release fraction for radionuclide release class i due to special release mechanisms (e.g., SGTR accidents or iodine releases from water pools late in the accident).

Each release fraction is defined by

$$rf_i = \frac{qR_i}{qI_i} ,$$ (Eq. 7.3)

where

qR$_i$ =   quantity (units: kg) of radionuclide release class i released to the environment,

qI$_i$ =   quantity (units: kg) of radionuclide release class i present in the core at the time the fission process ceases.

There is no correction for radioactive decay since this correction is made in the consequence calculation by MACCS.

The second part of the decomposition is a further subdivision of each release fraction in (Eq. 7.3) into their constituent parts. Specifically, each of these release fractions is expressed in the form

$$rf_{ci} = \prod_{j=1}^{nf(c)} rf_{cij} ,$$ (Eq. 7.4)

where c designates the individual release modes (i.e., c = v,e,h,l,s), nf(c) is the number of steps in the release path or important processes for release mode c, and rf$_{cij}$ is the release fraction for step or process j, radionuclide release class i, and release mode c.

For example, the pathway for the release from fuel in-vessel has three steps and a removal process, so nf(c) = 4. The three steps are the passage from the fuel to the vessel atmosphere, the passage from there to the containment, and the passage from the containment to the environment. Thus, the subdivision of the release from fuel in-vessel is represented by

$$rf_{vi} = \prod_{j=1}^{4} rf_{vij}$$
$$= FCOR_i * FVES_i * FCONV_i * (\frac{1}{DFE_i})$$ (Eq. 7.5)

where

FCOR$_i$ =   fraction of radionuclide release class i released from fuel to the vessel atmosphere,

FVES$_i$ =   fraction of radionuclide release class i released to the vessel atmosphere that is released from the reactor cooling system to the containment before or immediately after vessel breach,

FCONV$_i$ =   fraction of radionuclide release class i released to the containment from the reactor coolant system that is released to the environment in the absence of engineered safety features,

DFE$_i$ =   decontamination factor for radionuclide release class i for engineered safety features (e.g., sprays) for material released from the reactor coolant system.

Similar decompositions are defined for rf_{ei}, rf_{hi}, rf_{li} and rf_{si}.

The purpose of the decompositions shown in (Eq. 7.2) and (Eq. 7.4) is to represent the components of the release fraction calculations in terms of quantities for which distributions can be determined from the results of mechanistic calculations and experiments. In practice, the release fractions rf_{cij} shown in (Eq. 7.4) and illustrated in (Eq. 7.5) depend on the nature of the accident progression, and may differ from one type of accident to another. These differences in the accident progression are reflected in the APB definitions. For example, in the NUREG-1150 analyses there are two cases for the quantity FCOR$_i$ shown in (Eq. 7.5): high zirconium oxidation in-vessel and low zirconium oxidation in-vessel. That is, the value of FCOR$_i$ was sampled from one distribution provided by the experts when the zirconium oxidation during core degradation in the vessel was high, and from a different distribution when the zirconium oxidation was low. When this dependence is taken into account, the equation in (Eq. 7.4) becomes

$$rf_{ci} = \prod_{j=1}^{nf(c)} rf_{cij}(C_{cj}) \ , \qquad \text{(Eq. 7.6)}$$

where C_{cj} is a variable designating the particular set of conditions under consideration in the determination of rf_{cij} and hence rf_{ci}. In the representation for rf_{vi} shown in (Eq. 7.5), FCOR$_i$ corresponds to rf_{vi1} and so C_{v1} would designate whether the release under consideration involved high or low zirconium oxidation in the vessel. Typically, C_{cj} can be viewed as an integer variable taking on from 2 to 6 values, where each value corresponds to a different set of accident conditions.

When the representations in (Eq. 7.2), (Eq. 7.4), and (Eq. 7.6) are brought together, the following representation for release fractions to the environment is obtained:

7.5

$$rf_i = \sum_{c=v,e,h,1,s} [\prod_{j=1}^{nf(c)} rf_{cij}(C_{cj})]$$

(Eq. 7.7)

This decomposition provides the formalism for incorporating source term information derived from many sources into the individual NUREG-1150 plant studies.

7.3   Development of Source Term Data Base

To implement the release fraction decomposition in (Eq. 7.7) in the XSOR codes in a manner that reflects the uncertainty in the processes that determine the magnitude of the release, distributions must be developed for each factor rf_{cij} for each set of conditions C_{cj}. The analyses performed for the first draft of NUREG-1150 provided preliminary decompositions and an idea of which factors rf_{ci} were the largest contributors to the uncertainty in the source terms.

These decompositions were reviewed and revised as necessary by the analysis team, and preliminary decisions made about which were the more important factors. The more important factors were termed "issues." As the source term panel of outside experts did not have the resources to provide distributions for all the factors, this division into more important and less important factors was necessary. Possible conditions on which each issue might depend were also compiled.

When the expert panel convened, the decomposition of the release fractions into pathways (see Eq. 7.2) and the further decomposition of each pathway into factors (see Eq. 7.6) was reviewed with the panel and changed as they suggested. Next the division of the factors rf_{ci} into more important and less important classes was discussed with the panel. Since the panel would provide distributions for the more important factors (the issues) and their time was limited, there could be no wholesale movement of factors from the less important class to the more important class. However, adjustments were made until the panel was satisfied that they were considering the factors that were the most important to the magnitude of the release and the uncertainty in it. Then the conditions on which each factor depended were discussed by the panel until they came to an agreement on which conditions were important and which were not. For example, they decided that $FCOR_i$ in (Eq. 7.5) did not depend on the RCS pressure during core degradation, but that $FVES_i$ did.

Once the factors to be considered by the panel had been determined, and the dependency conditions for each decided, the panel set about its most time-consuming task: determining distributions for each release factor rf_{cij} for each condition C_{cj}. To do this, each expert on the team for a particular issue considered all the experiments, theoretical analyses, and mechanistic code calculations that he considered relevant. Each expert weighed the value of all the information and provided a subjective distribution giving the probability that the appropriate value to use for rf_{cij} falls in specified intervals for each C_{cj}. These distributions from each expert were combined to give one composite distribution to be used in XSOR. For each evaluation in the sample, typically about 200, XSOR uses one value from the distribution for rf_{cij} for each C_{cj} to compute a source term for each APB.

7.6

Distributions for the less important release factors were determined by the analysis staff based on the same types of information used by the panel of outside experts: mechanistic code results, experiments, etc. Personnel from NRC contractor laboratories were usually consulted, and every effort was made to ensure that the distributions adopted were sufficiently wide to reflect all approaches and different schools of thought.

Although plant conditions are generally best represented by continuous variables, for treatment in the XSOR framework these continua usually had to be broken up into a finite number of ranges. Each range was usually represented by the midpoint value of the range. Thus, C_{cj} could take on nR values denoted by

$$C_{cjk}, \ k=1, \ldots, nR, \qquad \text{(Eq. 7.8)}$$

and a probability distribution is required for rf_{cij} for each C_{cjk}. Each distribution is characterized by a function F_{cijk} such that, if $x_1 < x_2$ are two possible values for rf_{cij} for case C_{cjk}, then

$$F_{cijk}(x_2) - F_{cijk}(x_1) \qquad \text{(Eq. 7.9)}$$

is the subjective probability specified by the expert review process that the appropriate value to use for rf_{cij} falls between x_1 and x_2.

At the completion of the expert review process, a distribution F_{cijk} was available for each release fraction rf_{cij} and each case C_{cjk} associated with it. With this information, XSOR can calculate the release fractions for every APB for each observation in the sample. The other information required in (Eq. 7.1), timing, release heights, and release energies were estimated primarily at Sandia, based on plant data and the results of mechanistic code calculations. This information constituted the data base used for the estimation of the source terms shown. Volume 2, Part 4 of this report[7] provides the results of the expert elicitation process used to develop distributions for the source term analysis.

7.4   Mapping from Accident Progression Bins to Source Term Data Base

To permit a source term estimate by XSOR for each APB, there must be correspondence between accident progression bin properties and the conditions for which distributions are defined for each release factor. Each accident progression bin is defined by a vector of characteristics of the form

$$vAPB = [Ch_1, Ch_2, \ldots, Ch_{nCh}], \qquad \text{(Eq. 7.10)}$$

where nCh is the number of APB characteristics for the particular plant under consideration. In turn, each characteristic can take on 2 or more values, called attributes, that define the particular conditions associated with a given accident progression bin. As an example, Table 6-2 lists the 11 characteristics for Surry, and Table 6-3 lists the attributes for the first two of these

7.7

characteristics. For Surry, the eighth characteristic is the amount of in-vessel zirconium oxidation, which has two attributes: low zirconium oxidation (<40%) and high zirconium oxidation (>40%).

The link between the accident progression analysis and the source term analysis is a mapping, represented by a function F, from the vectors vAPB to the conditions used in the definition of the source term data base. In Sections 7.2 and 7.3, these conditions were represented by the variable C_{cj}. Notationally, all these conditions collectively can be represented by the vector

$$vC = [C_1, C_2, \ldots, C_{nCnd}] , \qquad \text{(Eq. 7.11)}$$

where nCnd is the total number of conditions used in the development of the source term data base and the variables C_j, j=1, ..., nCnd, correspond to the individual conditions (i.e., all the C_{cj}). The mapping F is defined by

$$\begin{aligned} F(vAPB) &= vC(vAPB) \\ &= [C_1(vAPB), C_2(vAPB), \ldots, C_{nCnd}(vAPB)] , \end{aligned} \qquad \text{(Eq.7.12)}$$

where $C_j(vAPB)$ is the value for condition j that results when the accident progression bin defined by vAPB is considered. As an example, if C_j was the condition that specified the level of in-vessel zirconium oxidation, then $C_j(vAPB)$ would be either low or high zirconium oxidation depending on the value of vAPB.

Sometimes the value for $C_j(vAPB)$ depends on only one of the characteristics in vAPB. This is the case with the zirconium example just given. In other cases, the value for $C_j(vAPB)$ may depend on several of the characteristics in vAPB. This dependency between $C_j(vAPB)$ and vAPB, as specified by the function F, was developed through interaction between the analysts responsible for the accident progression and source term analyses.

7.5   The XSOR Codes

The preceding sections have described a decomposition of radionuclide release fractions, the development of a data base for use in conjunction with this decomposition, and the definition of a mapping from accident progression bin characteristics to the source term data base. The XSOR[1] codes were developed to bring these activities together computationally to produce source terms of the form shown in (Eq. 7.1). The performance of the XSOR codes was compared to the STCP to assure that reasonable release fractions were calculated.[8]

The XSOR codes contain the source term data base described in Section 7.3 and implement the mapping F described in Section 7.4 from accident progression bin characteristics to conditions in the data base. Once this mapping is performed, appropriate values for use with the release fraction decomposition described in Section 7.2 are selected and release fractions are calculated with expressions of the form shown in (Eq. 7.7). In addition, timing parameters and energy

As described in Section 4.5, the integrated NUREG-1150 analyses use Monte Carlo procedures as a basis for uncertainty and sensitivity analysis. This involves propagating a Latin hypercube sample of the form shown in (Eq. 4.8) through the analysis performed for each plant. In general, this results in a different set of accident progression bins and different values for the source term variables for each sample element.

Notationally, the accident progression bins can be represented by

$$APB_{sk}, \ k=1, \ \ldots, \ nAPB(s) \ , \hspace{2cm} \text{(Eq. 7.13)}$$

where APB_{sk} is the kth accident progression bin obtained when the APET is evaluated for the sth sample element, and nAPB(s) is the total number of accident progression bins obtained for sample element s. As indicated in Section 6.5, each of the accident progression bins has a frequency $fAPB_{sk}$.

The XSOR code is used to obtain a source term estimate for each accident progression bin APB_{sk}. In doing this, XSOR uses variable values appropriate for the sth sample element, that is, XSOR uses the vector X_s as shown in (Eq. 4.8). As described earlier, the XSOR code contains the entire source term data base developed for the particular plant under consideration. Thus, XSOR contains distributions for the parameters used in release fraction estimation. The vector X_s for sample elements does not actually contain parameters used in release fraction estimation, rather, X_s contains pointer variables used to select parameter values from the source term data base distributions in XSOR. The XSOR code takes X_s and the associated accident progression bins shown in (Eq. 7.13) as input, determines the release fraction parameters specified by X_s, and then calculates a source term

$$ST_{sk}, \ k=1, \ \ldots, \ nAPB(s) \ , \hspace{2cm} \text{(Eq. 7.14)}$$

for each sample element. The resultant source terms ST_{sk} are of the form shown in (Eq. 7.1) with the addition of the subscripts s and k to specify sample element and accident progression bin, respectively.

7.6 Source Term Partitioning

The total number of source terms ST_{sk} generated in a single plant analysis was quite large and typically fell somewhere between 10,000 and 100,000. It was computationally impractical to perform a MACCS consequence calculation for each source term. Therefore, this large number of source terms was divided into a much smaller number (about 50) of source term groups, which formed the interface between the source term analysis and the consequence analysis. This division was based on the potential to cause early and chronic health effects and was implemented by the PARTITION[9] program. Each source term group was constructed so that it presented a similar set of conditions for consequence analysis.

The outcome of the source term partitioning was a sequence of source term groups

$$STG_\lambda, \ \lambda = 1, \ \ldots, \ nSTG \ , \qquad\qquad \text{(Eq. 7.15)}$$

where each source term group is a set of source terms that specify similar initial and boundary conditions for consequence analysis. These groups actually enter into the integrated plant analyses through two additional quantities that are also generated by PARTITION. The first of these is the matrix $P(APB \to STG)$ of transition probabilities from accident progression bins to source term groups appearing in (Eq. 4.3). The second is a mean source term

$$mST_\lambda, \ \lambda=1, \ \ldots, \ nSTG, \qquad\qquad \text{(Eq. 7.16)}$$

for each source term group. The mean source terms mST_λ are of the same form as those shown in (Eq. 7.1) and are obtained by weighting each source term in STG_λ by its frequency.

The partitioning process is described in detail in the user's guide for PARTITION.[9] As part of the consequence analysis, a MACCS calculation is performed for the mean source term mST_λ associated with each source term group.

7.7   Source Term Risk Results

As discussed in Chapter 2, the results of a risk analysis can be expressed as a set of triples R. The form of these triples shown in (Eq. 6.2) is appropriate for the discussion of the source term risk results. There are several ways in which such sets might be defined at the completion of the source term analysis. Further, given a particular definition, a different set R_s results for each sample element X_s.

One possibility is to define the R_s by

$$R_s = \{ \ (APB_{sk}, \ fAPB_{sk}, \ ST_{sk}) \ , \ k=1, \ \ldots, \ nAPB(s) \} , \qquad \text{(Eq. 7.17)}$$

where APB_{sk} represents the set of all accidents assigned to accident progression bin APB_{sk} for sample element s. As discussed in Section 4.5, the uncertainty results given by the R_s taken collectively can be shown with families of exceedance frequency curves and distributions of annual risks. An example of such a family of exceedance frequency curves for the iodine release fraction for internal initiators at Surry is shown in Figure 7-1. There is one curve for each of the 200 observations in the sample.

Another possibility is to define each R_s by

$$R_s = \{ \ (STG_{s\lambda}, \ fSTG_{s\lambda}, \ mST_\lambda) \ , \ \lambda=1, \ \ldots, nSTG \} \ , \qquad \text{(Eq. 7.18)}$$

where $STG_{s\lambda}$, represents the set of all accidents assigned to source term group λ for sample element s, $fSTG_{s\lambda}$ is the estimated frequency for source term group

for sample element s, and mST_λ is the mean source term for source term group λ shown in (Eq. 7.16). The frequency $fSTG_i$ is defined by the relationship in (Eq. 4.3) for each sample element. The set $STG_{s\lambda}$ is the union of the sets APB_{sk} for the accident progression bins assigned to source term group λ for sample element s; this assignment is summarized in the matrix P_s (APB → STG) shown in (Eq. 4.9). The characteristic source terms mST_λ assigned to the individual source term groups do not change from sample element to sample element and therefore do not contain the subscript s.
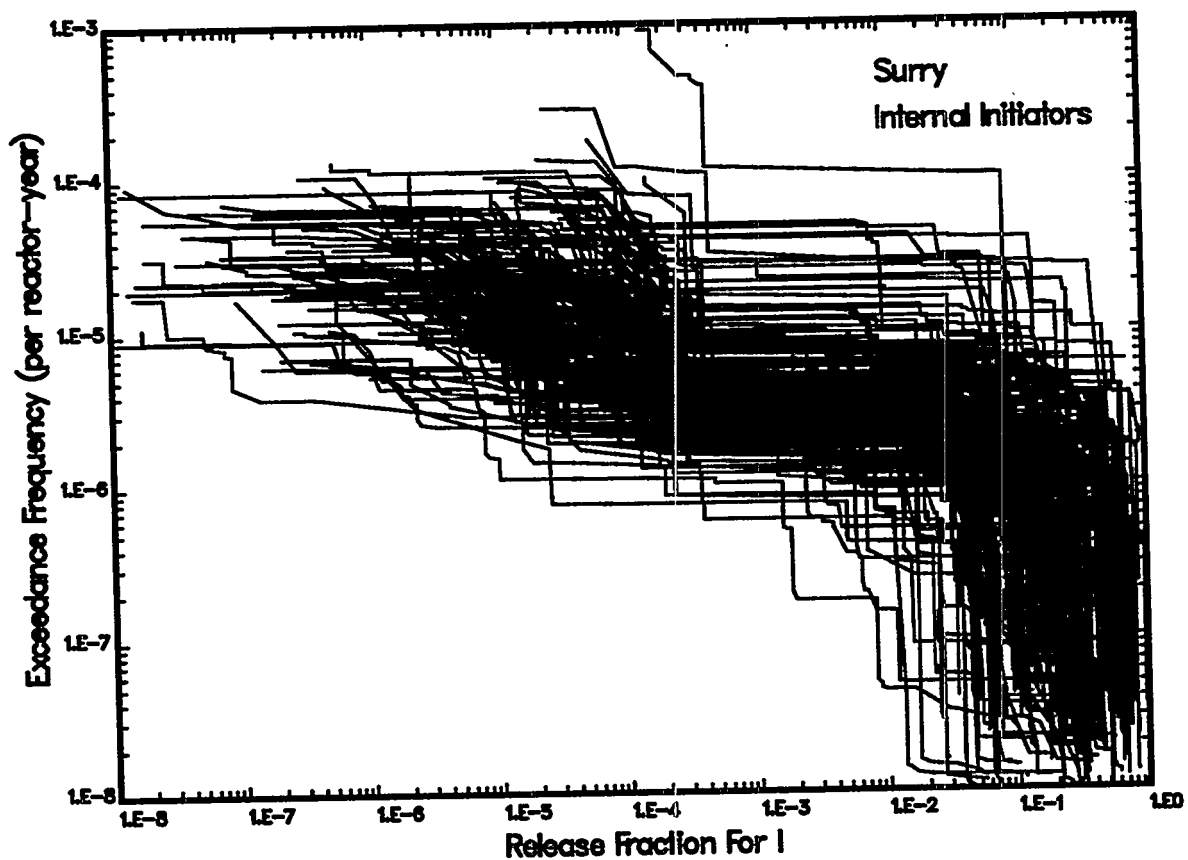
Figure 7-1 Exceedance frequency curves for the iodine release fraction for
internal initiators at Surry (from Fig. B.3-1 in Ref. 2).

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8.0 OFFSITE CONSEQUENCE ANALYSIS

8.1 Introduction

The severe reactor accident radioactive releases described in the preceding section are of concern because of their potential for impacts in the surrounding environment and population. The impacts of radioactive releases to the atmosphere from such accidents can manifest themselves in a variety of ways, such as early and delayed health effects, loss of habitability of areas close to the power plant, and economic losses. The fourth step in the NUREG-1150 risk analyses is the estimation of these offsite consequences, given the radioactive releases generated in the previous step of the analysis.

The principal steps in the offsite consequence analysis are:

- Assessment of pre-accident inventories of radioactive material;

- Analysis of the downwind transport, dispersion, and deposition of the radioactive materials released from the plant;

- Analysis of the radiation doses received by the exposed populations via direct (cloudshine, inhalation, groundshine, and deposition on skin) and indirect (ingestion) pathways;

- Analysis of the mitigation of these doses by emergency response actions (evacuation, sheltering, and relocation of people), interdiction of milk and crops, and decontamination or interdiction of land and buildings;

- Calculation of the health effects of the release, including:

  - Number of early fatalities and early injuries expected to occur within 1 year of the accident, and the latent cancer fatalities expected to occur over the lifetimes of the exposed individuals;

  - The total population dose received by the people living within specific distances (e.g., 50 miles) of the plant; and

  - Other specified measures of offsite health effect consequences (e.g., the number of early fatalities in the population living within 1 mile of the reactor site boundary).

Each of these steps will be discussed in the following sections.

The NUREG-1150 offsite consequence calculations were performed with Version 1.5 of the MACCS (MELCOR Accident Consequence Code System) computer code.[1-3]

8.2 Assessment of Pre-Accident Inventories

The radionuclide core inventories were calculated using the SANDIA-ORIGEN code.[4] For PWRs, the base calculation was performed for a 3412 megawatt (thermal) (MWt) Westinghouse PWR with an annual refueling cycle and an 80 percent capacity factor. The core contains 89.1 metric tons of uranium (MTU), is initially

enriched to 3.3 percent U-235, and is used in a 3-year cycle, with one-third of the core being replaced each year. The specific power is 38.3 MWt/MTU, which gives the burnups at the end of 3-year cycle at 11,183 megawatt-days (MWD)/MTU, 22,366 MWD/MTU, and 33,550 MWD/MTU for each of the three regions of the core.

For BWRs, the base calculation was performed for a 3578 MWt General Electric BWR-6 reactor. It also had an annual refueling cycle and an 80 percent capacity factor. The core contains 136.7 MTU and has initial enrichments of 2.66 percent and 2.83 percent U-235. The 2.66 percent fuel is used for both the 3-year cycle and the 4-year cycle, while the 2.83 percent is used only for the 4-year cycle. The fuel on 4-year cycles operates at roughly average power for the first three years and is then divided into two batches for the fourth year: half going to the core center (near average power) and half going to the periphery (about half of the average power). This complex fuel management plan yields five different types of discharged spent fuel and the inventory at the end of annual refueling includes the contributions of all fuel types.

The core inventory of each plant was calculated by multiplying the standard PWR or BWR core inventory described above by the ratio of plant power level to the power level of the standard plant. The 60 radionuclides considered to be of most importance to offsite consequences are placed in nine groups as listed in Table 7-1.

8.3   Transport, Dispersion, and Deposition of Radioactive Material

The MACCS code uses an empirical straight line Gaussian model for calculations of transport and dispersion of the plume that would be formed by the radioactive material released from the plant. These calculations use a sequence of successive hourly meteorological data from the reactor site for several days beginning at the release.[2] MACCS also calculates the rise of the plume vertically while it is transported downwind if the radionuclide release is accompanied by thermal energy. Actual occurrence and the height of the plume-rise depends on the thermal release rate and the ambient meteorological conditions at the time of the release.[5] Depletion of the plume by radioactive decay and dry and wet deposition processes during transport are taken into account. Radioactive contamination of the ground due to the dry and wet deposition processes is also calculated. These calculations are performed up to a very large distance, namely, 1,000 miles, from the reactor. Beyond 500 miles from the reactor, the deposition rate is artificially increased to ensure complete deposition of all radioactive material in particulate form and a complete accounting of these radionuclides. The noble gases are not deposited and ultimately leave the region. The impact of very dilute noble gases leaving the region is negligible. Thus, the entire impacted region for this study is the circular region with a 1,000-mile radius centered on the plant site.

The consequences for a given release of radioactive material depend on the ambient weather conditions, and so vary with the wind direction, time of day, season of the year, and so on. The wind direction is particularly important due to the variations in the population distribution, land use, and agricultural practice and productivity around the plant site. The MACCS code treats weather variability by calculating the consequences for many weather sequences. Each weather sequence is statistically selected from the plant's meteorological data

for an entire year to represent a class of weather sequences, and provides hourly wind speed, mixing, and precipitation values for the consequence calculation. The consequences are calculated for all 16 wind directions: for each direction, the probability of the consequence is the product of the weather sequence probability and the wind direction probability. The consequence evaluations with MACCS for this study generally utilized between 1,500 to 2,500 combinations of weather sequence and direction sector. This produces an equal number of pairs of magnitude and probability for each consequence measure analyzed. These collections of pairs of magnitude and probability for each consequence measure form the information set from which the exceedance curves are generated.

8.4   Calculation of Doses

MACCS calculates the radiological doses to the population resulting from several exposure pathways using a set of dose conversion factors.[6-8] During the early phase, which begins at the time of the radionuclide release and lasts about a week, the exposure pathways are the external radiation from the passing radioactive cloud (plume), contaminated ground, and radiation from the radionuclides deposited on the skin, and internal radiation from inhalation of radionuclides from the cloud and resuspended radionuclides deposited on the ground. Following the early phase, the long-term (chronic) exposure pathways are external radiation from the contaminated ground and internal radiation from ingestion and inhalation. The ingestion pathway includes foods directly contaminated during plume passage, milk from cows which ate contaminated forage, foods grown on contaminated soil, and contaminated water. The inhalation pathway treats previously deposited radionuclides which have been resuspended.

8.5   Mitigation of Doses by Emergency Response Actions

In the event of a large atmospheric release of radionuclides in a severe reactor accident, a variety of emergency response and long-term countermeasures would be undertaken on behalf of the public to mitigate the consequences of the accident. The emergency response measures to reduce the doses from the early exposure pathways include evacuation or sheltering (followed by relocation) of the people in the areas relatively close to the plant site and relocation of people from highly contaminated areas farther away from the site. The long-term countermeasures include decontamination of land and property to make them usable, or temporary or permanent interdiction (condemnation) of highly contaminated land, property, and foods that cannot be effectively or economically decontaminated. These response measures are associated with expenses and losses that contribute to the offsite economic cost of the accident.

The analysis of offsite consequences for this study included a "base case" and several sets of alternative emergency response actions. For the base case, 99.5 percent of the population within the 10-mile emergency planning zone (EPZ) participated in an evacuation. This set of people moved away from the plant site at a speed estimated from the plant licensee's emergency plan, after an initial delay (to permit communication of the need to evacuate), which was also estimated from the licensee's plan. The 0.5 percent of the population that did not participate in the initial evacuation was relocated within 12 to 24 hours after plume passage, based on the measured concentrations of radioactive material in the surrounding area and the comparison of projected doses with proposed

8.3

Environmental Protection Agency (EPA) guidelines.[9] Similar relocation criteria were used for the population outside the 10-mile planning zone.

For seismic initiators, the evacuation parameters were altered since the earthquakes were judged to affect the evacuation. It was estimated that for earthquakes in which the maximum peak ground acceleration (PGA) exceeds 0.6 g, there would be no effective evacuation and many structures would be uninhabitable. However, the population that would have evacuated is relocated after 24 hours. For earthquakes in which the maximum PGA does not exceed 0.6 g, the evacuation is degraded. The delay period (from the warning to the start of evacuation) is increased to 1.5 times its normal value, and the evacuation speed is decreased to half its normal value.

The shielding parameters were also modified for seismic initiators. For earthquakes in which the maximum PGA exceeds 0.6 g, it was assumed that the population within ten miles of the plant remained outdoors for a period of 24 hours and then were relocated. Thus, the shielding factors were those for the outdoor exposure. At greater than 10 miles, it was assumed that there was no earthquake damage and that the same shielding factors and relocation models used for the internal events would be applicable. For earthquakes in which the maximum PGA does not exceed 0.6 g, the normal activity shielding factors were modified to account for the effect that broken windows would have on the people remaining indoors.

Several alternative emergency response assumptions were also analyzed in this study's offsite consequence and risk analyses. These included:

- Evacuation of 100 percent of the population within the 10-mile emergency planning zone;

- Indoor sheltering of 100 percent of the population within the EPZ (during plume passage) followed by rapid subsequent relocation after plume passage;

- In lieu of evacuation or sheltering, only relocation from the EPZ within 12 to 24 hours after plume passage, using relocation criteria described above.

In each of these alternatives, the region outside the 10-mile zone was subject to a common assumption that relocation was performed based on comparisons of projected doses with EPA guidelines (as discussed above).

8.6 Health Effects Modeling

The potential early health effects of radioactive releases are fatalities and morbidities (injuries) occurring within about a year in the population receiving acute and high radiological doses from the early exposure pathways. The potential delayed health effects are fatal and nonfatal cancers that may occur in the exposed population after varying periods of latency and continuing for many years; and various types of genetic effects that may occur in the succeeding generations stemming from radiological exposures of the parents. Both early and chronic exposure pathways would contribute to the latent health effects.

8.4

The early fatality models currently implemented in MACCS are based on NUREG/CR-4214.[10] Three body organs are used in the early fatality calculation: red bone marrow, lung, and lower large intestine (LLI). The organ-specific early fatality threshold doses used are 150 rems, 500 rems, and 750 rems, and LD_{50}* values used are 400 rems, 1,000 rems, and 1,500 rems to the red marrow, lung, and LLI, respectively. The current models reflect a reduced effectiveness of protracted inhalation doses in causing early death; they also take the benefits of medical treatment into account.

The early injury models implemented in MACCS are also threshold models and are similar to those described in NUREG/CR-4214. The candidate organs used for the current analysis are the stomach, lungs, skin, and thyroid.

The latent fatal and nonfatal cancer models are nonthreshold and linear-quadratic models taken from NUREG/CR-4214 and are based on the BEIR III Report.[11] However, only a linear model was used for latent cancer fatalities from the chronic exposure pathways since the quadratic term was small compared to the linear term because of low individual doses from these pathways. The specific organs used were red bone marrow (for leukemia), bone, breast, lung, thyroid, LLI, and others (based on the LLI dose representing the dose to the other organs).

Population exposure has been treated as a nonthreshold measure; truncation at low individual radiation dose levels has not been performed.

8.7 Products of Offsite Consequence Analysis

The product of this part of the analysis is a set of offsite consequence measures for each source term group. For NUREG-1150, the specific consequence measures discussed include early fatalities, latent cancer fatalities, total population dose (within 50 miles and total), and two measures for comparison with NRC's safety goals, average individual early fatality risk within 1 mile and average individual latent fatality risk with 10 miles. In NUREG-1150, results of the offsite consequence analysis are displayed in the form of complementary cumulative distribution functions (CCDFs), as shown in Figure 8-1. As discussed in Section 4.4, these curves are constructed from sequences of the form

$$(pW_n, cSTG_{1mn}), \; n = 1, 2, \ldots, nW, \qquad \text{(Eq. 8.1)}$$

where pW_n is the probability of occurrence for weather trial n, $cSTG_{1mn}$ is the consequence value associated with source term group 1 for consequence measure m and weather trial n, and nW is the number of weather trials.

The uncertainty in the parameters of the offsite consequence analysis was not included in the overall uncertainty analysis performed for the NUREG-1150 PRAs, although variability due to hourly variations in meteorological conditions is included. Examples of uncertainty/sensitivity studies for reactor accident consequence models are available elsewhere.[12-14]

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*Only 50% of the population receiving this dose will survive.

8.5
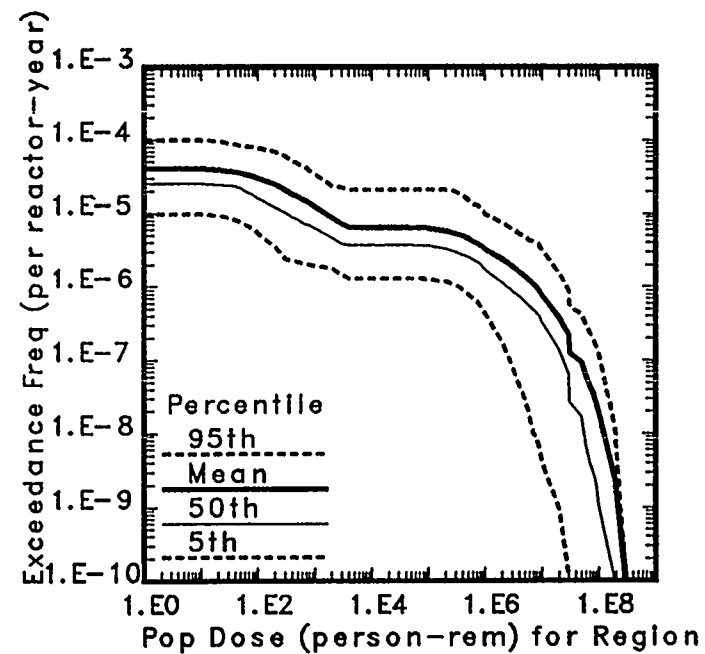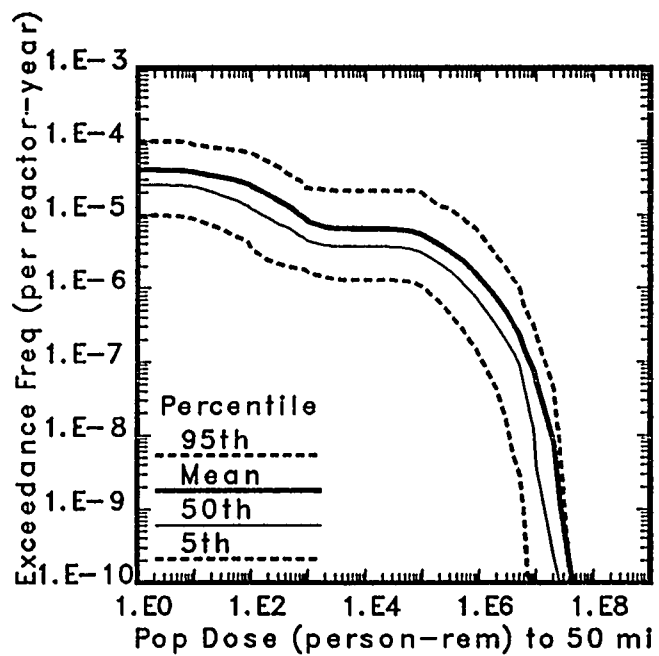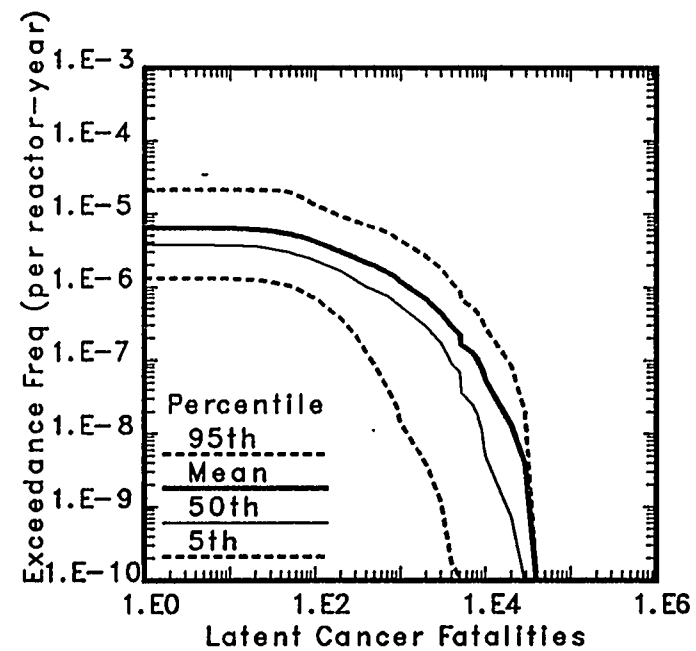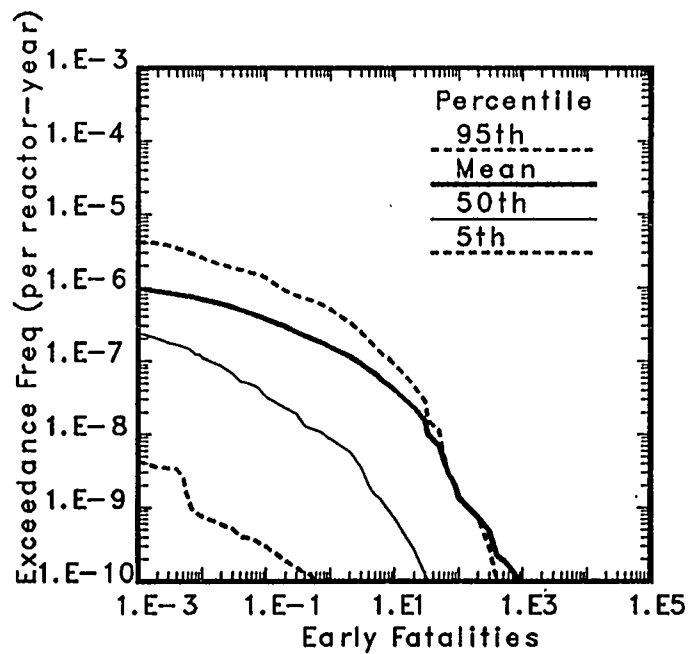
Figure 8-1   Example Display of Offsite Consequences Complementary Cumulative Distribution Function

The MACCS code is documented in NUREG/CR-4691,[1-3] and the specific MACCS input used is given in Part 7 of Volume 2 of this report.[15]

As discussed in Chapter 2 and illustrated at the end of Section 4.4 for consequence analysis, the basic conceptual representation for risk in NUREG-1150 involves sets of ordered triples. The contribution of consequence analysis to these risk sets is information of the form shown in (Eq. 8.1). The typical way to display consequence risk information is as exceedance frequency curves, where consequence value appears on the abscissa and the frequencies at which individual values are exceeded appear on the ordinate. An example of such a curve appears in Figure 4-2. As shown in Figure 4-4, a family of these curves results from the uncertainty propagation procedure used in NUREG-1150. Since consequence variables are not sampled, the variability in the curves in Figure 4-4 comes from factors that affect the parts of the analysis before consequence analysis.

Construction of the curves in Figure 4-2 and 4-4 uses the vector fSTG of source term group frequencies shown in (Eq. 4.3) and the consequence results shown in Figure 8-1. In the construction of Figure 4-4, there is a new frequency vector fSTG for each sample element. For the calculation of annual risks, each of the curves in Figure 8-1 can be reduced to a single expected risk. This yields the matrix cSTG shown in (Eq. 4.4). Since consequence variables were not sampled, the matrix cSTG does not change from sample element to sample element. As can be seen in (Eq. 4.9), what does change are the terms by which cSTG is multiplied to obtain annual risk. The calculations in (Eq. 4.9) lead to distributions of annual risk of the form shown in Figure 4-5. The results shown in Figure 4-5 are the outcome of reducing each of the curves in Figure 4-4 to a single number.

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9.0 CHARACTERIZATION AND COMBINATION OF UNCERTAINTIES

9.1 Overview

An important characteristic of the probabilistic risk analyses conducted in support of NUREG-1150 is that they explicitly include an estimation of the uncertainties in core damage frequency and risk. These uncertainties exist because of our incomplete understanding of reactor systems and severe accident phenomena.

There are four steps in the performance of uncertainty analyses. Briefly, these are:

- determine the scope of the uncertainty analysis,

- define the specific parameters to be included in the analysis,

- develop probability distributions for these parameters, and

- combine the uncertainties and analyze the results.

Important sources of uncertainty exist in all four stages of the risk analysis. In this study, the total number of parameters about which uncertainty exists is very large. Resource limitations required that only the most important uncertain parameters could be included in the integrated risk analyses. An understanding of which uncertainties could be among the more important to risk was obtained from previous PRAs, discussion with those conducting research into severe accident processes, limited sensitivity analyses, and the PRAs performed for the first draft of NUREG-1150.

The parameters thought to be the most important in determining the uncertainty in risk are called "issues." Issues involve processes and events for which the uncertainties were estimated to be large and important to risk and for which there are no widely accepted models. Probability distributions for issues were determined by panels of outside experts. The issues considered by these panels are listed in Table 9-1.

In order for uncertainties in accident phenomena to be included, probability distributions had to be developed for specific parameters that were used in the accident frequency, accident progression, and source term analyses. The offsite consequence analysis was not included in the uncertainty analysis. None of these constituent analyses were at the same level of detail as the detailed or integrated mechanistic computer codes. Thus, the uncertain input parameters used in this study are "high level" or summary parameters. For many of the physical phenomena involved, there are no widely accepted, complete models that link the fundamental physical quantities to the summary parameters. This is largely due to lack of knowledge and understanding; it leads to what is referred to in this study as modeling uncertainties. In addition, the values of some important physical or chemical parameters are not well known. These are referred to as data uncertainties. Both types of uncertainties were included in the study and no consistent effort was made to differentiate between the effects of the two types of uncertainties.

Probability distributions for input parameters were developed by a number of methods. Distributions for the input parameters having the largest uncertainties and believed to be of the greatest importance to risk were determined by panels of experts. The experts used a wide variety of techniques to generate probability distributions, including reliance on detailed code calculations, extrapolation of existing experimental and accident data to postulated conditions during the accident, and complex logic networks. Probability distributions were obtained from the expert panels using formalized procedures designed to minimize bias and maximize accuracy and scrutability of the experts' results. These procedures are described and results are given in Volume 2 of this report.[1] Probability distributions for parameters believed to be of less importance to risk were generated in a less formal manner by analysts on the project staff with the assistance of experts from NRC contractor laboratories using sources of information similar to those utilized by the expert panels.

A stratified Monte Carlo method, Latin hypercube sampling,[2] was used to create a sample from the probability distributions defined for uncertain input parameters. The sample observations were propagated through the constituent analyses to produce probability distributions for core damage frequency and risk. Monte Carlo methods produce results that can be analyzed with a variety of techniques, such as regression analysis. Such methods easily treat distributions with wide ranges and can incorporate correlations between variables. Latin hypercube sampling provides for a more efficient sampling technique than straightforward Monte Carlo sampling while retaining the benefits of Monte Carlo techniques. It has been shown to be an effective technique when compared to other, more costly, methods.[3] Since many of the probability distributions used in the risk analyses are subjective distributions, the composite probability distributions for core damage frequency and risk must also be considered subjective.

The results of the risk analysis and its constituent analyses are subjective probability distributions as described in Chapter 3. The quantities involved are given in (Eq. 3.4) and (Eq. 4.5). With Latin hypercube sampling, the probability distributions are estimated with a limited number (about 200) of calculations of risk, each calculation being equally likely. That is, for the uncertainty analysis about 200 values of rC_{sm} in (Eq. 3.4) are generated.

9.2

Table 9-1.
Issues Considered by Expert Panels

- **Accident Frequency Analysis Panel**

  Failure probabilities for check valves in interfacing-system LOCAs (Event V) (PWRs)

  Physical effects of containment structural or vent failures on core cooling equipment (BWRs)

  Innovative recovery actions in long-term accident sequences (PWRs and BWRs)

  Pipe rupture frequency in the component cooling water system (Zion)

  Use of high-pressure service water system as source for drywell sprays (Peach Bottom)

- **Reactor Coolant Pump Seal Performance Panel**

  Frequency and size of reactor coolant pump seal failures (PWRs)

- **In-Vessel Accident Progression Panel**

  Probability of temperature-induced reactor coolant system hot leg failure (PWRs)

  Probability of temperature-induced steam generator tube failure (PWRs)

  Magnitude of in-vessel hydrogen generation (PWRs and BWRs)

  Mode of temperature-induced reactor vessel bottom head failure (PWRs and BWRs)

- **Containment Loading Panel**

  Containment pressure increase at reactor vessel breach (PWRs and BWRs)

  Probability and pressure resulting from hydrogen combustion before reactor vessel breach (Sequoyah and Grand Gulf)

  Probability and effects of hydrogen combustion in reactor building (Peach Bottom)

Table 9-1 (continued)

- **Molten Core-Containment Interactions Panel**

  Drywell shell meltthrough (Peach Bottom)

  Pedestal erosion from core-concrete interaction (Grand Gulf)

- **Containment Structural Performance Panel**

  Static containment failure pressure and mode (PWRs and BWRs)

  Probability of ice condenser failure due to hydrogen detonation (Sequoyah)

  Strength of reactor building (Peach Bottom)

  Probability of drywell and containment failure due to hydrogen detonation (Grand Gulf)

  Pedestal strength during concrete erosion (Grand Gulf)

- **Source Term Expert Panel**

  In-vessel retention and release of radioactive material (PWRs and BWRs)

  Revolatilization of radioactive material from the reactor vessel and reactor coolant system (early and late) (PWRs and BWRs)

  Radioactive releases during high-pressure melt ejection/direct containment heating (PWRs and BWRs)

  Radioactive releases during core-concrete interaction (PWRs and BWRs)

  Retention and release from containment of core-concrete interaction radioactive releases (PWRs and BWRs)

  Ice condenser decontamination factor (Sequoyah)

  Reactor building decontamination factor (Peach Bottom)

  Late sources of iodine (Grand Gulf)

9.2   Types of Uncertainty

The major assumption or belief that underlies the structure of the NUREG-1150 risk assessments is the importance of separating stochastic uncertainty from subjective uncertainty. Stochastic uncertainty occurs because the system under consideration (e.g., a nuclear power plant and its environment) can behave in many different ways. Subjective uncertainty exists because our current state of knowledge is incomplete. Thus stochastic uncertainty is a property of the system under study while subjective uncertainty results from an imperfect human knowledge base. The importance of making this distinction has been emphasized by many authors.[4-9]   Subjective uncertainty is often·divided into model uncertainty and parameter uncertainty. In this study, model uncertainties associated with phenomenological issues and data uncertainties associated with inputs to these models are represented by the uncertainties in the parameters that form input to the PRA logic models. Thus, in this study, all subjective uncertainties (i.e., model and parameter) are represented by subjective parameter uncertainties. The uncertainties that arise from the PRA models themselves (i.e., the structure of the event trees and fault trees, number of issues addressed, aggregation) has not been addressed in this study. The definitions used in this study for subjective and stochastic uncertainty are described in the following two paragraphs.

> Subjective parameter uncertainty designates the uncertainty that results from the impreciseness of the quantitative estimates for the input parameters used in the phenomenological and logical models chosen for use in the analysis. This is referred to as subjective uncertainty because it is a function of the state of knowledge of the analysts rather than a property of the system. As an example, this uncertainty may characterize the precision with which a quantity may be estimated from available data.

> Stochastic uncertainty designates the uncertainty that results from the intrinsic variability of the system under consideration. Ideally, stochastic uncertainty is a property of the system under study, while subjective uncertainty is a property of the analysts performing the study. Phenomena may not be inherently stochastic, but can be considered stochastic within the resolution of a particular analysis and/or within the resolution of our ability to understand nature. Although stochastic uncertainty is a property of the system, its characterization can be dependent on the structure and level of detail of the model used to describe this system. Stochastic uncertainty occurs when a particular event in a PRA model obeys probabilistic laws and does not have a definite deterministic outcome. That is, for repeated trials, it is not expected that the identical result would always occur.

Both types of uncertainties were included in the study. For example, there is stochastic uncertainty resulting from the fact that a pump will not start every time. However, the uncertainty in the precise failure rate is a subjective parameter uncertainty.

In the NUREG-1150 PRAs, the structure of each analysis allows for stochastic uncertainty. For example, each question with more than one nonzero branch in the event trees used in the accident frequency and accident progression analyses expresses a stochastic uncertainty. If there was not subjective uncertainty, specific fixed values could be used for the probability of each branch. Conceptually, these event trees define a strategy based on importance sampling for the incorporation of stochastic uncertainty. In contrast, subjective uncertainty enters the analysis through the definition of probability distributions for quantities in the analysis such as branch probabilities in the event trees. Subjective uncertainty is also used to characterize events for which different outcomes are hypothesized, however, only one outcome is correct (i.e., there is no stochastic uncertainty) and based on our current state of knowledge we cannot be certain a priori which is the correct outcome. For this type of event, if the same accident occurred a large number of times the same outcome would always result. In the accident progression analysis this type of event is typically represented by a multibranch question in the event tree with only one branch being used for any given observation. For example, a question with two outcomes A and B will be handled by having some sample members follow outcome A and other sample members will follow outcome B. That is, for any given sample member only one branch will be taken. If the subjective probability of outcome A is 0.10, then 10% of the sample members will follow outcome A, and only A; and 90% will follow B and only B. Sample members having outcome A may be considered as belonging to a universe in which A is the only possible outcome, and those having B belong to a universe in which only B is possible. This type of sampling is referred to as "0/1" sampling, because the probability of following a path is zero for some sample members and unity for others, but never anything in between. The "in-between" case, where both branches have probabilities greater than 0 and less than 1 is referred to as split fraction sampling. (The two probabilities must sum to 1.0, of course.)

The division of uncertainty into types is not always a clear-cut process. Often experts are divided in their opinion as to whether an uncertain issue should be treated as subjective (i.e., "0/1" type) or stochastic. Those experts who have a background in probability and statistics tend to view more issues as stochastic than do those having backgrounds in deterministic analysis. If some experts believe an issue to be truly "0/1" and others believe it to be stochastic, then the resulting aggregated distribution will be a hybrid. Sample members falling within the subjective part are sampled "0/1" and those falling within the stochastic part are sampled by split fractions. An example is temperature-induced large hot-leg failures in PWRs. Some experts believed that the event would either always happen or would never happen, and their uncertainty was as to which outcome would be true. Others thought that the event would sometimes happen, but under similar initial and boundary conditions might not happen, and their uncertainty was as to the frequency with which the event would occur. If a sample member falls at either end of the distribution the event will occur with probability zero or one. However, if the sample member falls in the middle of the distribution, the event will have a split fraction for occurrence.

The use of expert opinion to characterize and quantify the uncertainty in important events modeled in the PRA is discussed in the next section.

9.3 Use of Expert Opinion

The methodology used in the expert judgment process for NUREG-1150 was designed to obtain subjective estimates of unknown physical quantities and frequencies in a manner that best uses the available expertise and accurately reflects the collective uncertainty about these values. Several principles guided the application of expert opinion methods:

1. The assessments should be limited to issues on which alternative sources of information such as experimental or observational data, or validated computer models are not available.

2. The issues analyzed using expert judgment should have the potential to make a significant impact on the estimates of risk and uncertainty in risk.

3. The decomposition of complex issues into simpler assessments is made in order to improve the quality of the resulting information.

4. Issues should be presented to the experts without ambiguity and without the potential for preconditioning or biasing responses.

5. Experts should be trained in the practice of expressing knowledge and beliefs as probability distributions.

6. Discussion of issues and alternative beliefs should take place in structured and controlled meetings that encourage the exploration of alternative beliefs while inhibiting pressure to conform.

7. Elicitation of expert opinion should be conducted using techniques and instruments that reflect the state of the art in subjective probability assessment.

8. The aggregation of judgments from various experts should preserve the uncertainty that exists among alternative points of view. Equal weight should be assigned to the assessment for each expert to represent the uncertainty completely.

NUREG-1150 does not attempt to reduce uncertainty in risk analysis, nor is it an attempt to find a best estimate. This study is an attempt to produce an unbiased picture of uncertainty in risk. The study tries to discover the range in risk inherent in the range of plausible assumptions about phenomenology and initial and boundary conditions. The risk corresponding to the most (subjectively) plausible assumptions has a higher likelihood of being accepted by a randomly chosen expert in accident phenomena. The risk corresponding to less plausible assumptions nevertheless has some likelihood of being accepted by any expert, and may indeed be the most acceptable for some experts. Experts are sometimes wrong, and the "true" risk could lie outside the ranges found in this study.

9.3.1 Steps to Elicit Expert Judgment

The principles identified above, the criticism of the draft NUREG-1150 expert judgment efforts, and the findings of precursor studies employing expert judgment[10,11] provided guidance for the design of the NUREG-1150 expert judgment elicitation process. The process evolved into ten steps:

1. Selection of issues;
2. Selection of experts;
3. Elicitation training;
4. Presentation and review of issues;
5. Preparation of expert analyses by panel members;
6. Discussion of analyses;
7. Elicitation;
8. Recomposition and aggregation;
9. Review by the panel of experts;
10. Documentation.

These steps are also shown in Figure 9-1.

The methodology was implemented in a three-meeting format, with much additional work being accomplished between meetings. Steps 1 and 2 were accomplished before the first meeting of the expert panel. Step 3, elicitation training, took place in the first meeting, which lasted one-half day. The presentation and review of issues, Step 4, was done during the second meeting, which, in order to reduce travel costs, took place immediately after the first meeting. Step 5 was accomplished between the second and third meetings (in some cases the expert panels met for additional discussions during this time). Discussion and elicitation, Steps 6 and 7, occurred in the third meeting, which usually took place three months after the first and second meetings (the accident sequence frequency group and the structural response group met two months after the first two meetings). The final steps, 8, 9, and 10, were accomplished after the third meeting.

9.3.2 Selection of Issues

The NUREG-1150 program attempts to show the range and distribution of risk due to uncertainty in the inputs. Some of this uncertainty is phenomenological, some is stochastic, and some is because of limited availability of data. There are an enormous number of inputs, and all are uncertain to some extent. It was thus impossible to treat all questions and issues with the same degree of thoroughness. In selecting issues to be brought before the expert panels, the following points were considered:
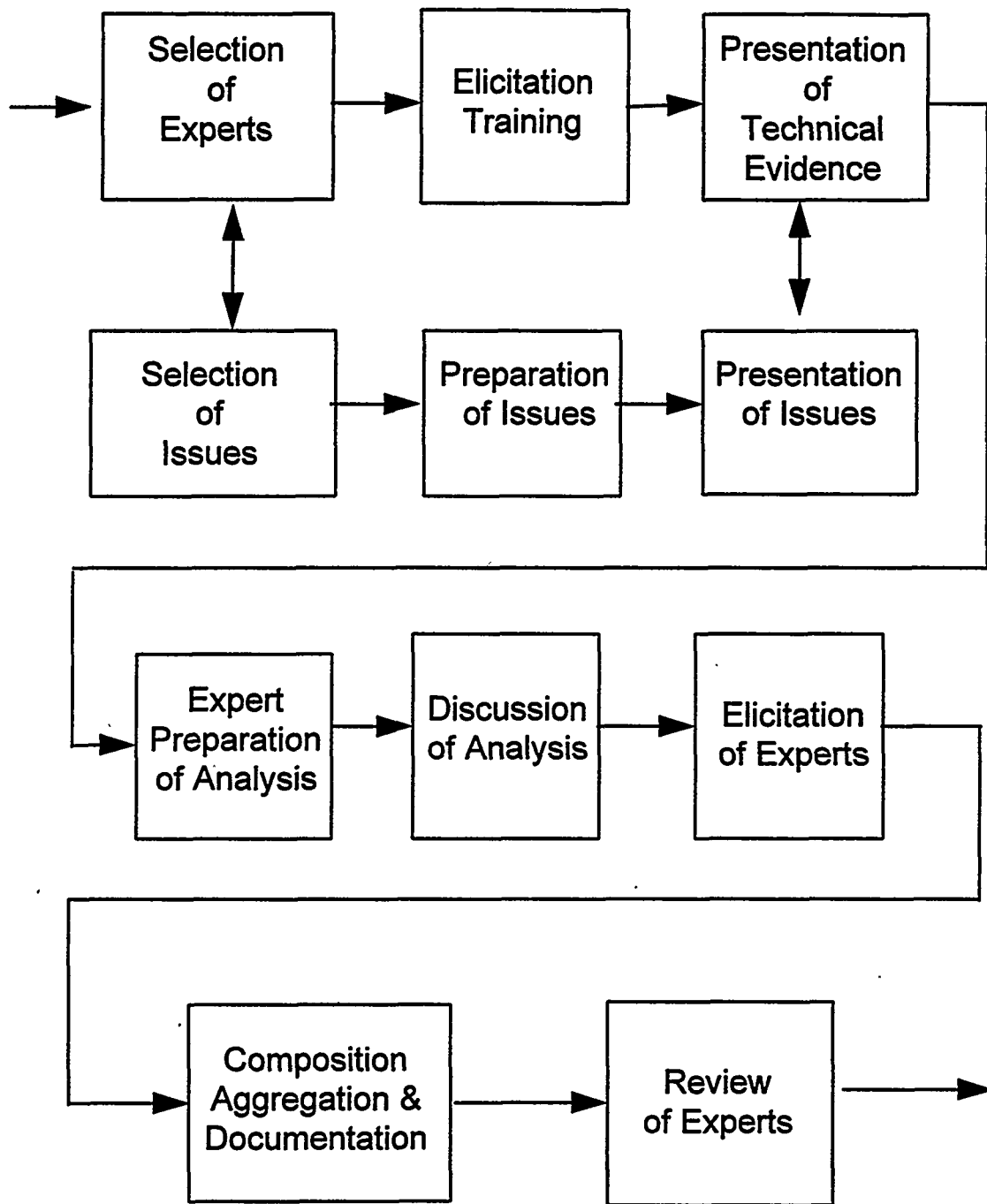
Figure 9-1   Principal steps in Obtaining Expert Opinion
(Figure A-15 (p. A-46) in Appendix A of NUREG-1150)

- <u>High impact on risk</u>. A parameter should have a large effect on the magnitude of risk to be included as an issue. If a parameter was highly uncertain, but variation across its entire range would not cause a big change in risk, there would be little need for a detailed treatment. The likely impact on risk was determined by the outcome seen in the draft version of NUREG-1150, by smaller scale side calculations, by the opinions of the expert panels, and by examination of previous PRAs.

- <u>Interest within the reactor safety community</u>. Some parameters were thought not to be major determinants of risk or uncertainty in risk, but nevertheless involved processes or events that had been the subject of intense investigation and debate.

- <u>To improve on the treatment in Draft NUREG-1150</u>. For some parameters that were not important in the draft version, it was recognized that the treatment there was less than optimum. Such parameters might be included to determine whether an improved treatment would change those conclusions.

- <u>High impact on uncertainty</u>. If the uncertainty in a parameter appeared unlikely to affect the mean value of risk, but seemed likely to have a significant effect on the uncertainty in risk, it was treated as an issue if feasible.

Parameters meeting any of these criteria were included in a preliminary list of issues presented to each panel of experts, along with reasons for their inclusion. A list of parameters not selected as issues was also presented, along with reasons for their exclusion. The expert panel was asked to review the list of issues, and to add or delete issues. The expert panels were the same ones that would be asked to quantify these uncertain issues. An understanding of the limited time and resources available generally militated against an unwarranted or overly generous expansion of the issues.

Those issues that were selected for quantification by the external expert panels fell into three broad classes: issues affecting the sequence frequency calculation, issues affecting the response of the containment and its systems, and issues affecting the radiological source term. There were more issues affecting containment than for the other areas, and there was a further breakdown into issues related to the in-vessel phenomenology, containment loads, structural response, and molten core-concrete interactions. Tables 9-2 through 9-6 show the issues presented to the containment and radiological source term expert panels, along with the reasons for including the issue.

Table 9-2
Issues Presented to the In-Vessel Panel

Issue No.	Title	Reason for Inclusion
1	Temperature-induced PWR hot leg failure	Large hot leg failure could preclude direct containment heating; depressurizes RCS and precludes SGTR
2	Temperature-induced PWR SGTR	SGTR gives direct path to environment, with large release of radionuclides
3	In-vessel hydrogen production in BWRs	Hydrogen burning has potential for causing release to environment
4	Temperature-induced bottom head failure in BWRs	Mode of bottom head failure determines subsequent accident progression
5	In-vessel hydrogen production in PWRs	Hydrogen burning has potential for causing release to environment
6	Temperature-induced bottom head failures in PWRs	Mode of bottom head failure determines subsequent accident progression

Table 9-3
Issues Presented to the Containment Loads Panel

Issue No.	Title	Reason for Inclusion
1	Hydrogen phenomena at Grand Gulf	Early failure of drywell or wetwell has potential for causing large source term
2	Hydrogen burn at vessel breach at Sequoyah	Early failure of containment or bypass of ice condenser has potential for causing large source term
3	BWR reactor building failure due to hydrogen burns	Bypass of reactor building has potential for increasing source terms
4	Loads at vessel breach at Grand Gulf	Failure of containment at vessel breach has potential for causing large source terms
5	Loads at vessel breach at Sequoyah	Same as Issue 4
6	Loads at vessel breach at Surry	Same as Issue 4
7	Loads at vessel breach at Zion	Same as Issue 4

Table 9-4
Issues Presented to the Structural Response Panel

Issue No.	Title	Reason for Inclusion
1	Static failure pressure and mode at Zion	Containment failure is the most important determinant of source terms
2	Static failure pressure and mode at Surry	Same as Issue 1
3	Static failure pressure and mode at Peach Bottom	Same as Issue 1
4	Reactor building bypass at Peach Bottom	Bypass of reactor building has potential for allowing large release of radionuclides
5	Static failure pressure and mode at Sequoyah	Same as Issue 1
6	Ice condenser failure due to detonations at Sequoyah	Failure or bypass of ice condenser has potential for large source terms
7	Drywell and wetwell failure due to detonations at Grand Gulf	Failure of drywell bypasses suppression pool. Failure of wetwell allows large release to environment
8	Pedestal failure due to erosion at Grand Gulf	Pedestal failure is a major factor in subsequent accident progression

Table 9-5
Issues Presented to the Molten Core-Concrete Interaction Panel

Issue No.	Title	Reason for Inclusion
1	Mark I drywell melt-through at Peach Bottom	Drywell meltthrough bypasses suppression pool; controversial issue
2	Mark II containment failure via pedestal failure at Grand Gulf	Pedestal failure could lead to early containment failure; controversial issue

Table 9-6
Issues Presented to the Source Term Panel

Issue No.	Title	Reason for Inclusion
1	In-vessel fission product release and retention	Release and retention are major determinants of source term
2	Ice condenser DF at Sequoyah	Ice condenser is principal decontamination mechanism in blackouts
3	Revolatilization from RCS/RPV	Revolatilization could negate effects of high retention; highly uncertain issue
4	CCI release	If in-vessel release is low, CCI release could be high; uncertain issue
5	Release of RCS and CCI species from containment	Aerosol agglomeration may be major source of cleanup in blackout; highly uncertain issue
6	Late sources of iodine at Grand Gulf	Appeared as important issue in Draft NUREG-1150
7	Reactor building DF at Peach Bottom	Natural decontamination processes could reduce source term; uncertain and controversial issue
8	Release during direct containment heating	Uncertain and controversial issue; direct heating is also associated with early containment failure

9.3.3 Selection of Experts

Experts were chosen to ensure a balance of viewpoints. To this end, experts from industry groups, engineering and consulting firms, the federal government, and the national laboratories were included in the panel.

9.3.4 Elicitation Training

Training in probability assessment techniques is an integral part of the expert opinion methodology used in NUREG-1150. Each panel of experts that participated in the expert opinion process attended a half-day training session. This session constituted the first meeting of each panel. The training was given by consultants from the field of probability assessment and decision analysis. For example, the trainer for the Source Term Panel was Professor Ward Edwards of the University of Southern California.

The purpose of training in probability assessment is to facilitate the elicitation process. Experts in various fields of science are often not trained in probability theory and the techniques of presenting their results in the form of probability distributions. The expertise possessed by the scientists and engineers on the panels is called substantive expertise and thus they are called substantive experts. Expertise about the expert opinion elicitation process is called normative expertise. Both substantive expertise and normative expertise are required for a successful expert opinion process.

During probability training, the substantive experts are exposed to various techniques for expert opinion elicitation and the difficulties that accompany it. This training helps the substantive experts to express their knowledge in the form of probabilities. A by-product of the training is that the experts become more comfortable with the concept of subjective probability and more confident in expressing their beliefs in the form of probability distributions.

9.3.5 Training Topics

The training sessions conducted for NUREG-1150 covered several related topics. These topics included the expert opinion process itself and the need for expert opinion, the elicitation techniques, and the decomposition of complex issues.

Each training session began with an overview of the goals of the expert opinion process and background material on the development of that process. The process was reviewed in some detail so that the substantive experts would be aware of what would be required of them and how their elicitations would be used. Because the formal use of expert opinion was new to many of the participants, some were initially uneasy with the concept of expert opinion and the uses that it might be put to. Gaining the confidence of these experts through familiarization with the process was essential to the success of the expert opinion effort.

There are many different types of assessments that might be required of the experts. The type of assessment depends upon the nature of the physical quantity or phenomena under study. During the training sessions, the experts were introduced to assessment instruments for continuous quantities, discrete quantities, zero-one events, and dependent events.

Psychological aspects of probability elicitation received much attention in the training because failure to recognize and deal with psychological biases can impair the quality of the resulting assessments. One of the psychological aspects discussed is the tendency to give subjective probability distributions that are too narrow and thus understate the uncertainty or, conversely, overstate knowledge. This phenomena is often called "overconfidence", since the effect is the expressed probability distribution implies greater certainty than is warranted. Other psychological aspects of subjective probability assessment that were discussed include anchoring, which is the tendency to assume an initial position and fail to give sufficient credit to other sources of information; representativeness, which is the tendency to give too much credit to other situations that are similar in some aspects but not others; the tendency to overestimate the probabilities of rare events; and problems with group behavior such as personality dominance. Whenever possible, examples of these difficulties were presented and the experts being trained were asked to participate in demonstrations.

Problem decomposition was the last major segment of the training session. Problem decomposition is the process of creating a model of a complex assessment that allows the experts to make a series of simpler assessments. The simpler assessments are mathematically recomposed through the model. Experimental studies[12,13] have shown that decomposition often improves the accuracy of assessments. Decomposition also provides a form of self documentation since the expert's thought process is made explicit in the decomposition.

9.3.6 Presentation of Issues

During the second meeting, plant analysts presented the issues to the expert panel. The purposes of the presentations were to ensure that there was a common understanding of the issue being addressed; ensure that the experts would be responding to the same elicitation question; permit unimportant issues to be excluded and important issues to be included; allow modification or decomposition of the issue; and provide a forum for the discussion of alternative data sources, models, and forms of analysis. If appropriate, the presentation included a suggested decomposition of the problem.

Plant analysts usually presented the suggested decompositions without suggested probabilities or distributions to avoid preconditioning or biasing the experts. For many of the issues, the proposed decomposition brought about lively discussions that illuminated the alternative approaches to analyzing the issue. The plant analysts also presented data sources, models, and reports that were relevant to the issue, and provided references to other sources of information.

Capturing uncertainty in the experts' opinions requires that the various experts be permitted to follow alternative analyses. Since the process was designed to take advantage of the diversity of approaches, experts were encouraged to seek their own decompositions or to modify decompositions that were suggested by the analysts. Criticism of the decompositions was encouraged and the experts were assisted in producing decompositions that better matched their interpretations of the issues.

9.3.7 Preparation and Discussion of Analyses

Two or three months were allowed between the initial presentations of the issues and the elicitation sessions. During this period, the experts studied the issues. Some experts chose to alter the proposed decompositions or create new decompositions and made preliminary evaluations of the subjective probabilities represented in their decompositions of the issues. The elicitation meeting provided a forum for discussion of alternative views of the issue. Presentations from both the panel members and invited observers of the meetings were encouraged. These sessions generated a substantial amount of discussion and interchange of information that often led the experts to make revisions of their prepared analyses. In some instances, the panel members prepared documentation that amounted to brief reports. It became apparent in the elicitation sessions that this interchange was an important source of information for the experts.

9.3.8 Elicitation

The discussion of each issue was followed by elicitation meetings between each substantive expert and a team composed of a normative expert and a plant analyst. Documentation of the experts' assumptions and reasoning was produced during the elicitation meetings. However, in a few cases where there were more experts to be elicited than available normative experts, two experts were elicited in a single session.

The elicitation sessions served several purposes. The first was to obtain from the experts their decomposition and probability distributions for the parameters involved. The experts were also required to explain their reasoning and their sources of information.

The role of the normative experts was to assist the expert in codifying the experts' beliefs and to ensure that the assessment was complete and consistent in a probabilistic sense so that the assessments could be recomposed at a later time. The role of the plant analyst was to ensure that technical reasoning was complete and to answer questions about how the results on this issue would be used in the plant analysis and how this issue related to other issues. Much of the documentation of the experts' assumptions and reasoning was completed during the assessment meetings. However, some follow-up work was necessary after the elicitation sessions to fill in voids in the logic provided by the experts, or to obtain values that were incomplete.

9.3.9 Recomposition and Aggregation of Results

Each member of the expert panels produced a distribution for each case of each issue. For some issues, several dependent variables were requested, and a separate distribution was elicited for each variable. If all the experts had worked with identical case structures, and if all had produced their results in the same form, the task of aggregation would have been simply a matter of taking the numerical average of all the distributions for each case. However, some experts used different case structures. On some issues, the experts expanded the case structure beyond what was tractable in the accident progression event trees or the XSOR codes. On some issues, experts gave their results in different forms.

9.17

The case structure had to be simple enough to be implemented in the containment event trees and XSOR codes and that the case structure and dependent variables be the same between experts. If the case structure was impractically large and complex, it was reduced if possible by an analysis of variance (ANOVA). The ANOVA compared the variance in the dependent variable attributable to the differences between cases and the variance attributable to the differences among experts to the unexplained variance in the dependent variable. For many issues it was found that the differences between some cases were not significant compared to the differences between experts, that is, that some parts of a large and complex case structure had little effect on the dependent variable. A mathematical procedure was then used to determine which cases could be safely combined.

After each of the experts' distributions was placed in the same format, they were aggregated by averaging. The experts' outputs were almost always in the form of cumulative distribution functions (CDFs), that is, curves or tables of the probability that the independent variable would be no greater than some specific value. The aggregation was carried out by averaging all the experts' probability values for each value of the independent variable. The aggregated results were thus also CDFs.

9.3.10   Review

Following recomposition, modification, and change of format, as required, the results of the elicitation and expert's reasoning were written up in a standard format. The complete documentation of each issue was then returned to each panel expert, for his review. This review process ensured that potential misunderstandings were identified and resolved and that the documentation correctly reflected the conclusions and judgment of the expert.

9.3.11   Documentation

Clear, comprehensive documentation is crucial for ensuring that the expert opinion process is accepted as credible. Users and reviewers of the results must be able to trace the development of aggregated assessments, including any manipulation of the assessments needed for aggregation. To this end, the issue discussions were recorded on video tape and individual elicitation sessions were recorded on audio tape. Each expert was encouraged to document the rationale for his conclusions in detail. An overview of the expert's reasoning was obtained verbally at the time of the elicitation. In many cases the experts also provided written documentation that included results of computer models evaluated solely for this purpose.

9.4 References

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APPENDIX A

DESCRIPTION OF SUITE OF CODES USED TO CALCULATE RISK

A.1   Introduction

The purpose of Appendix A is to give the reader a general overview of the network of codes used in the Level II/III portion of the NUREG-1150 analyses. This appendix is an adaptation of material presented in Reference 1. The codes used in these analyses and the various input and output files will be discussed. Figure A-1 shows the suite of codes used to calculate risk in the NUREG-1150 analyses. For each code the various input and output files are shown and the flow of data from one code to the next is diagramed. The analysis is divided into the following 6 areas for purposes of discussion: input from the Level I analysis, the Latin Hypercube sample, the accident progression analysis, the source term analysis, the consequence analysis, and the integrated risk analysis. For each of these areas, the general process being performed, the codes used to perform the analysis, and the input and output files are discussed. While user guides for many of the major processing codes used in this study have been published, similar user guides for many of the preprocessors and postprocessors shown in Figure A-1 do not exist and listings of these codes have not been included in this report. However, similar versions of these processor codes were used in the study described in Reference 1 and listings of many of these codes are included in that report. Because it is possible that different code versions were used in the two different studies, the codes may be slightly different.

A.2   Input From Level I Analysis

The TEMAC[2] code is used to calculate the Level I accident sequence frequencies and to perform certain uncertainty and sensitivity analyses on the Level I results. After the cut sets from the Level I accident sequences are rearranged to form the plant damage states (PDSs) used in the Level II/III analysis, the code is used to perform the same calculations on the PDSs. For the Level II/III analysis, certain particular characteristics of the PDSs may be important for determining certain subtle details of the accident progressions; however, they may not be important enough to warrant defining new PDSs. The cut sets composing a PDS are grouped into sub-sets that have the characteristics of concern and each such sub-set is called a "sub-PDS." In order to calculate the conditional probabilities of the sub-PDSs with respect to the original PDS for inclusion as question branch probabilities in the accident progression event tree (APET), the cut sets in each PDS that have the characteristic of concern are identified and the TEMAC subroutine called "TEMAC4" is used to calculate the conditional probabilities and their distributions.

This calculation is performed in the following manner:

(1)   TEMAC input files from the Level I analysis are modified to include only those variables important for determining the PDS frequencies and their uncertainties, the sub-PDSs conditional probabilities, and any Level I variables used directly in the Level II/III analysis.
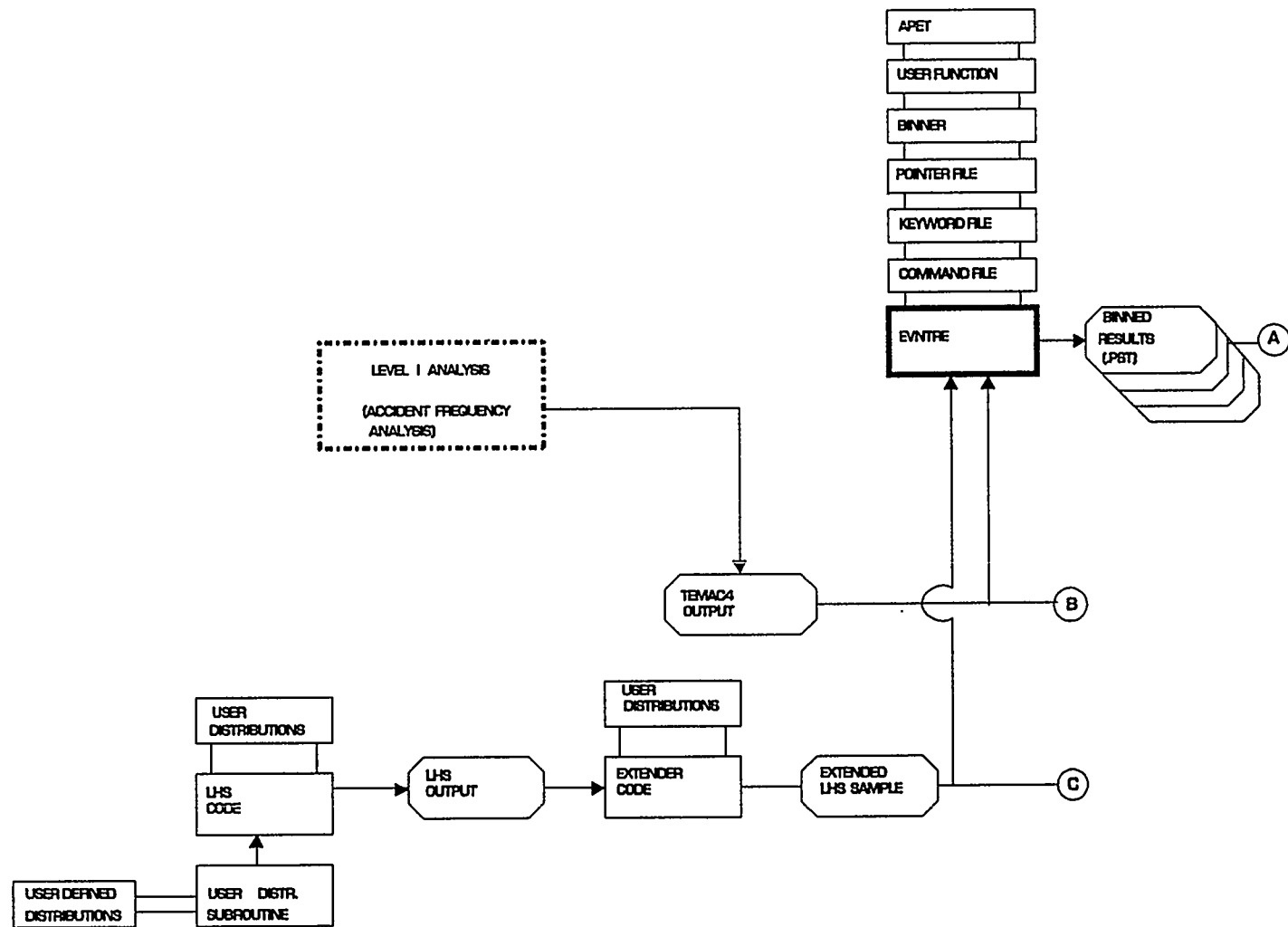
Figure A-1a   NUREG-1150 Level II/III PRA Calculational Scheme
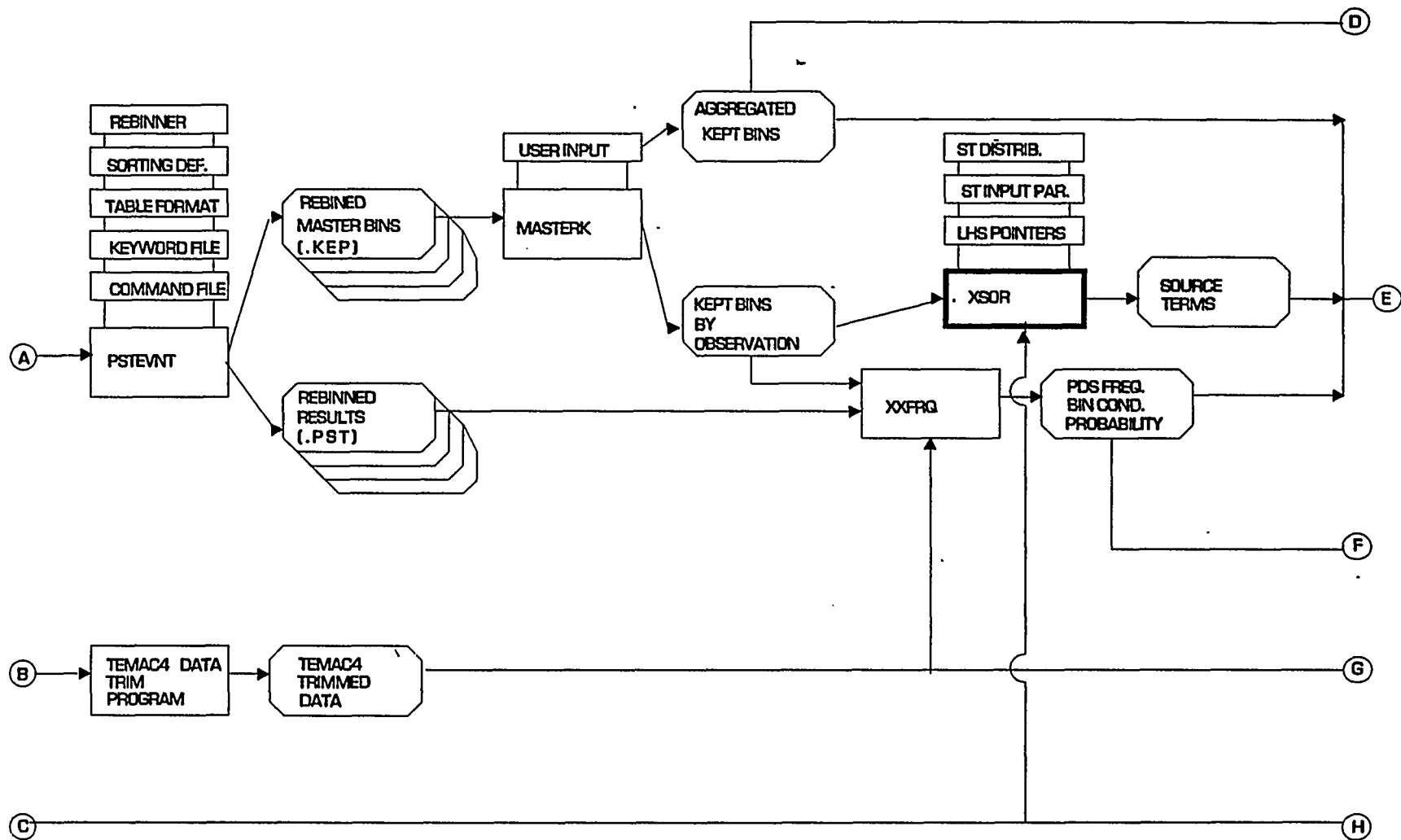
Figure A-1b NUREG-1150 Level II/III PRA Calculational Scheme
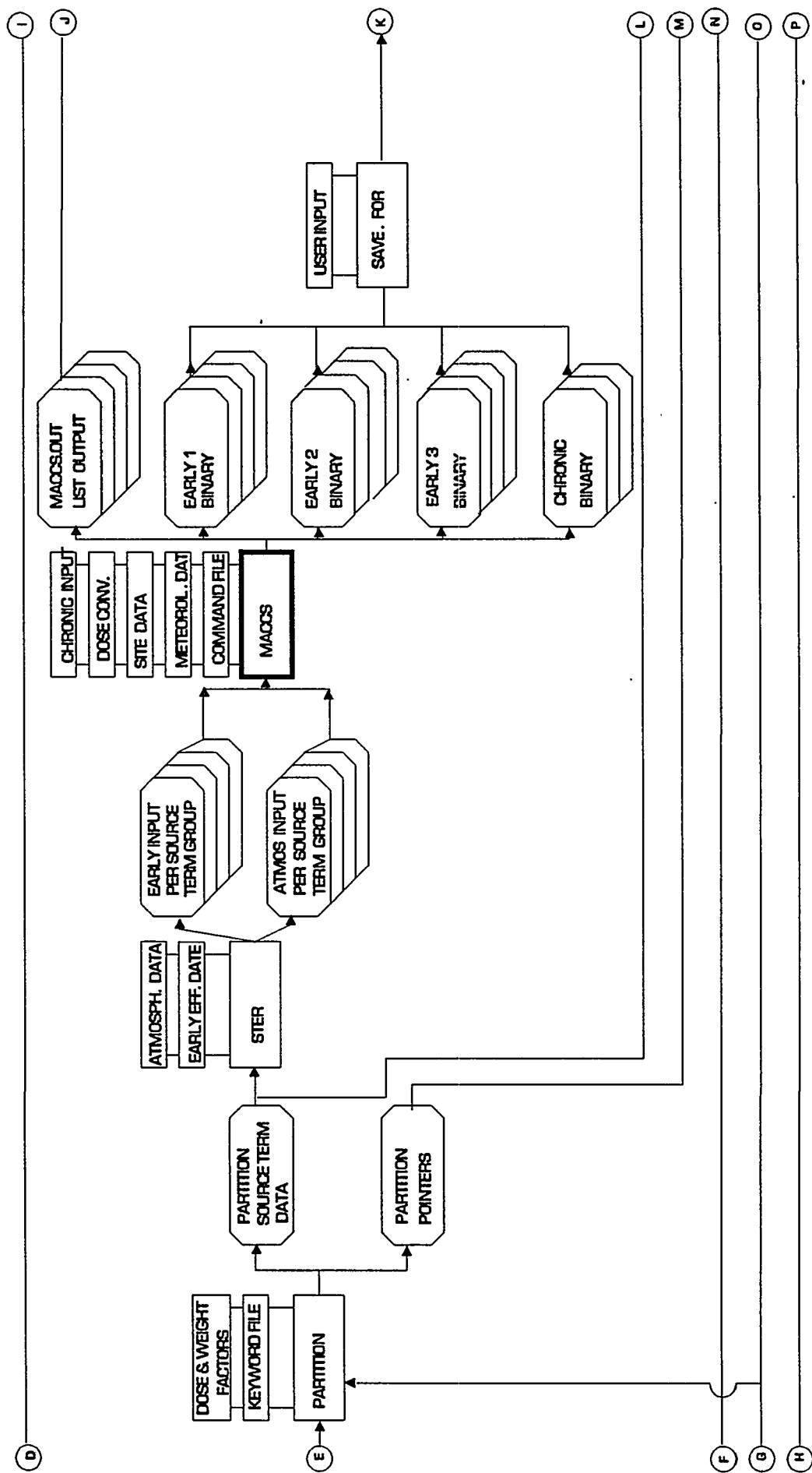
Figure A-1c NUREG-1150 Level II/III PRA Calculational Scheme
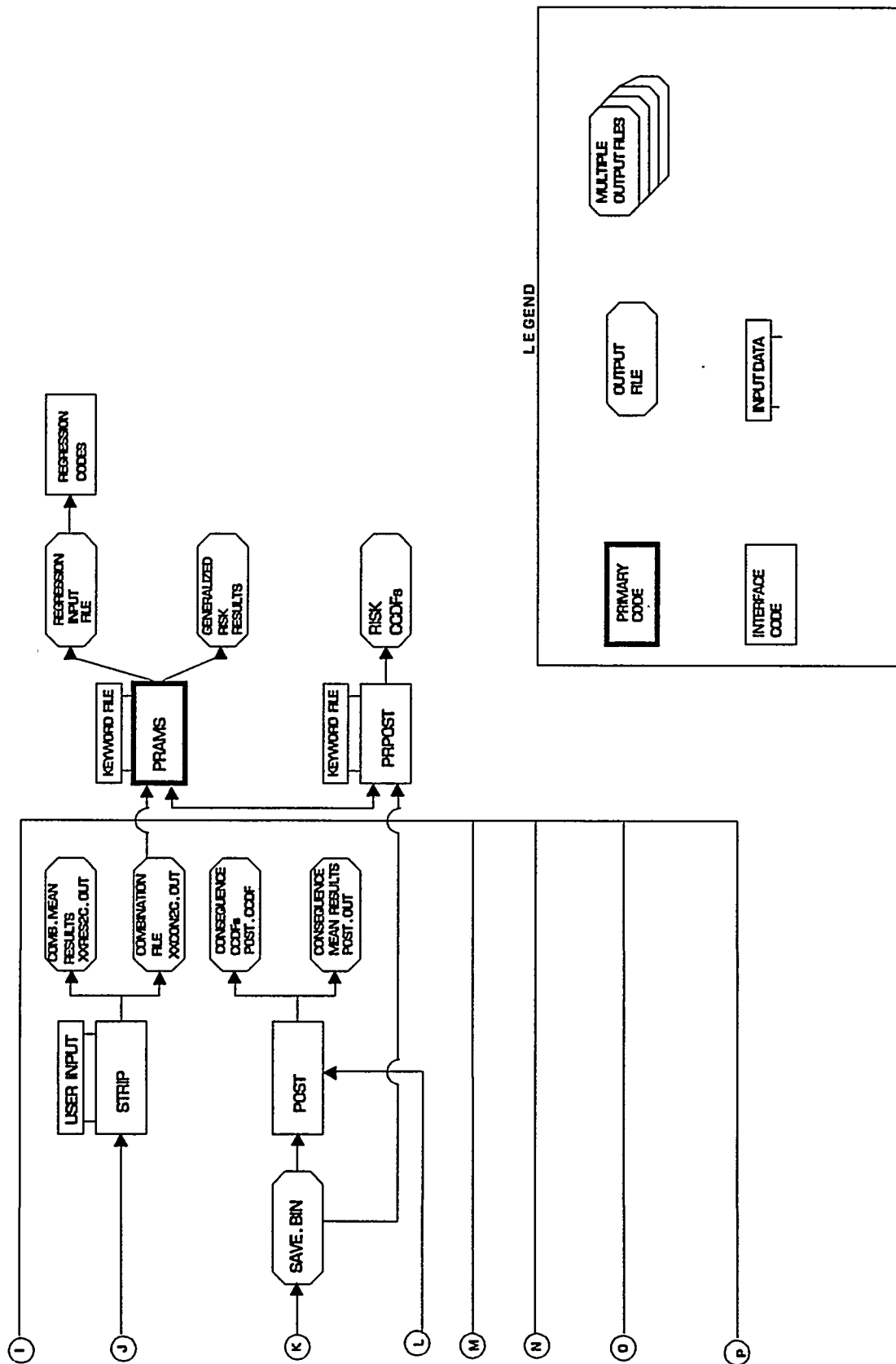
Figure A-1d   NUREG-1150 Level II/III PRA Calculational Scheme

LEGEND

PRIMARY CODE

OUTPUT FILE

MULTIPLE OUTPUT FILES

INPUT DATA

INTERFACE CODE

REGRESSION CODES

REGRESSION INPUT FILE

GENERALIZED RISK RESULTS

RISK CCDFs

KEYWORD FILE

PRAMS

KEYWORD FILE

PRPOST

COMB. MEAN RESULTS XVRESSC.OUT

COMBINATION FILE XVCON2C.OUT

CONSEQUENCE CCDFs POST.CCDF

CONSEQUENCE MEAN RESULTS POST.OUT

USER INPUT

STRIP

POST

SAVE.BIN

I   J   K   L   M   N   O   P

(2)   A TEMAC4 input file is prepared defining the groups of cut sets for which conditional probabilities need to be determined. See "LEVEL I ANALYSIS" in Figure A-1a.

(3)   The TEMAC code is run using the TEMAC4 subroutine. See "LEVEL I ANALYSIS" in Figure A-1a.

(4)   The TEMAC4 output contains a listing of both the PDS frequencies and the conditional probabilities of the sub-PDSs with respect to their respective PDSs on an observation basis (i.e., complete probability distributions are calculated for each conditional probability). See "TEMAC4 OUTPUT" file in Figure A-1a.

(5)   The TEMAC4 output is trimmed to include only the PDS frequency distributions. The sub-PDS conditional probabilities are used only in the accident progression event tree. See "TEMAC4 DATA TRIM PROGRAM" and "TEMAC4 TRIMMED DATA" file in Figure A-1b.

A.3   Latin Hypercube Sample

In order to perform an integrated assessment of the uncertainty in the risk, the uncertainty in the input parameters used in the analysis must be represented and propagated through the analysis. The technique used in this analysis is that of stratified Monte Carlo sampling. The particular method used is called "Latin Hypercube" sampling (LHS).[3] The LHS sample includes all of the important variables from the Level I analysis that determine the PDS frequencies and the sub-PDS conditional probabilities, Level I variables that are also used directly in the Level II/III analysis, and the variables used specifically in the accident progression analysis and the source term analysis.

A more detailed discussion of the construction of the LHS sample can be found in the appendices to the plant volumes.[4-8]

This calculation is performed in the following manner:

(1)   The initial Latin Hypercube sample is formed using the LHS code. See "LHS CODE" and "LHS OUTPUT" in Figure A-1a.

(a)   For any parameters that have certain standard distributions available to LHS, the distribution parameters are read in directly. See "USER DISTRIBUTIONS" in Figure A-1a.

(b)   A FORTRAN subroutine is constructed to: (1) calculate within the LHS code any distributions that are defined using data tables and (2) for parameters whose distributions are functions of the distributions of other parameters, the subroutine outputs code for inclusion in the LHS EXTENDER code to indicate what parameters will be used in the calculation. See "USER DISTR. SUBROUTINE" in Figure A-1a.

(2)   The final LHS sample is formed using the LHS EXTENDER code. This code contains the formulas for calculating the distributions of any

parameters that are functions of the distributions of other parameters and also allows the user to input into the final LHS sample any other distributions (such as the offsite power recovery distributions) that were not included in the initial LHS sample. See "EXTENDER CODE" and "EXTENDED LHS SAMPLE" in Figure A-1a.

A.4   Accident Progression Analysis

In order to determine all the unique ways an accident can evolve and to group these accident progressions using characteristics important for determining the source terms, an accident progression event tree (APET) is used. This APET defines the accident evolution in terms of a series of questions about the events that can happen during the accidents. The EVNTRE code[9] is used to analyze this event tree. The output of this code is a set of accident progression bins (APBs) and their conditional probabilities with respect to the PDSs from which they arise.

The PSTEVNT code[10] is then used to allow the analyst to regroup the EVNTRE output based on subsets of the characteristics used in the original binning process. This occurs when the analyst originally specified more characteristics for the initial binning than needed for the source term or consequence analysis. This is usually done for one of two reasons: (1) it may be necessary to look at more detailed results before a final grouping can be determined, or (2) there may be specific characteristics not used in the source term or consequence analysis that the analyst wants to examine.

The MASTERK code creates lists of unique bins across all PDSs based on the output from PSTEVNT. Two types of output files are created by MASTERK: (1) a list of unique bins across all PDSs and across all observations and (2) a list of the unique bins across all PDSs for each observation.

Finally the XXFRQ code is used to combine the results from all the individual PDS analyses (i.e., PSTEVNT runs) into one file. The output from XXFRQ contains the following information: (1) the plant damage state, (2) the PDS frequency, (3) the list of bins that arise from that PDS and (4) the conditional probability associated with each bin. This block of information (i.e., 1 through 4) is repeated for each PDS. All of this information is provided for each observation. (The letters XX are used to refer to this code in a general sense. When referring to the actual code used in a particular plant analysis, the XX is replaced with letters used to describe the plant. For example, SURFRQ was used in the Surry analysis.)

This calculation is performed in the following manner:

(1)   The EVNTRE code evaluates the APET in order to delineate the accident progression paths arising from each PDS and then to calculate the conditional probability associated with each path. These paths are then grouped into accident progression bins based on characteristics either important to determining the source term or interesting to the analyst for other reasons. A set of keywords is used to specify the calculations to be performed. See "EVNTRE

A.7

CODE," "KEYWORD FILE," and "APET" in Figure A-1a. Listings of the APETs are provided in Appendix A of the plant volumes.

(a)   The extended LHS sample and the TEMAC4 output file provide the distributions for the parameters used in the APET. These parameters are used to: (1) directly represent the conditional probabilities of the question branches in the APET or (2) used in subsidiary calculations to determine which branch is taken for those cases where the branch is not probabilistically determined.

(b)   The LHS pointer file tells EVNTRE where to place the sampled parameter values in the event tree. See "POINTER FILE" in Figure A-1a.

(c)   A FORTRAN subroutine is used to perform any subsidiary calculations using parameters defined in the APET. See "USER FUNCTION" in Figure A-1a. Listings of the User Functions are provided in Appendix A of the plant volumes.

(d)   Boolean logic is used for defining the accident progression bins in terms of the answers to specific questions in the APET. See "BINNER" in Figure A-1a. Listings of the binners are provided in Appendix A of the plant volumes.

(e)   The output is a list of accident progression bins by LHS sample observation and their conditional probabilities. See "BINNED RESULTS" in Figure A-1a.

(2)   The PSTEVNT code is then used to regroup the accident progression bins resulting from the original EVNTRE binning into those bins to be used in the source term evaluation or to sort the output in various ways that might be interesting to the analyst. See "PSTEVNT CODE" in Figure A-1b.

(a)   Boolean logic is used to define the characteristics to be used in the final binning in terms of the answers to specific questions in the APET. See "REBINNER" in Figure A-1b. Listings of the rebinners are provided in Appendix A of the plant volumes.

(b)   The user specifies the calculations to be done, any sorts desired, and the format of the output. See "KEYWORD FILE," "SORTING DEF.," and "TABLE FORMAT" in Figure A-1b.

(c)   The two forms of the output are provided: (1) a list of all the unique APBs for each observation and (2) a list of all the unique bins by observation and their conditional probabilities. See "REBINNED MASTER BINS" and "REBINNED RESULTS," respectively in Figure A-1b.

(3) The MASTERK code then combines the results of the PSTEVNT run for each PDS into one file and makes lists of the unique bins across all PDSs. See "MASTERK CODE," and "USER INPUT" in Figure A-1b.

     (a) A master list of all the unique bins occurring in the analysis from all observations is formed. See "AGGREGATED KEPT BINS" in Figure A-1b.

     (b) A list of all unique bins by observation is formed. See "KEPT BINS BY OBSERVATION" in Figure A-1b.

(4) Finally, the XXFRQ code associates each PDS and its frequency with the accident progression bins arising from that PDS and their conditional probabilities on an observation basis into one file by combining the TEMAC4 trimmed data and the rebinned EVNTRE results. See "XXFRQ CODE" and "PDS FREQ. BIN COND. PROBABILITY" in Figure A-1b.

A.5 Source Term Analysis

The XSOR[11] code calculates for each unique bin a source term using a parametric model. The source term parameters to be used and their values are based on the accident progression bin characteristics. The source term consists of the release fractions for nine radionuclide groups for each of two release segments. For each release segment the following additional information is supplied based on the accident progression characteristics: the start time of the release, the duration of the release, the energy of the release, and the height of the release. In addition, for each source term, a warning time is also specified. This calculation is done for each unique bin for each observation. The term XSOR refers to the class of parametric source term codes. A different code was used in each plant analysis taking into account unique features of the plant and the accidents that can potentially occur at the plant. The first few letters from the plant name are used to identify the code used for a particular plant analysis. For example, SURSOR was used in the Surry analysis. The XSOR codes are described in Reference 11 and a listing of the XSOR code for each plant is provided in Appendix B of each plant volume.

The PARTITION code[12] is then used to group the source terms from all observations. This grouping is based on an estimate of the early and latent health effects of each source term. The early health effects are estimated using weights generated from a set of consequence calculations using different levels of Iodine-131 releases and site specific data. The latent health effects are estimated using weights generated from a set of consequence calculations where each calculation uses the inventory of one of 60 radionuclides analyzed in the MACCS code and site specific data. The only emergency response measures taken into account in determining the early health effects for initial grouping purposes are hot spot and 24-hour relocation. No emergency response measures are taken into account for the latent effects. These groups are divided into subgroups on the basis of evacuation timing and frequency-weighted mean source terms are calculated for the groups and subgroups. Offsite consequences are calculated using the mean source term for each subgroup; these consequences are then assigned to each source term (i.e., accident progression) in the subgroup.

In the remaining portion of this appendix, the term "source term group" actually refers to the subgroup.

This calculation is performed in the following manner:

(1) Source terms are determined by the XSOR code with options specified by the analyst. See "XSOR CODE," "ST INPUT PAR.," and "SOURCE TERMS" in Figure A-1b.

   (a) In addition to the list of accident progression bins to be evaluated and the extended LHS sample, distributions for the source term parameters and pointers to the LHS variables representing the source term parameters are read in. It should be noted that the actual distributions for the source term parameters were not used in the extended LHS sample. Variables with uniform distributions ranging from 0 to 1 were used to represent these parameters in the extended LHS sample; these variables are then used in XSOR to select values from the actual distributions. See "ST DISTRB." and "LHS POINTERS" in Figure A-1b.

(2) The PARTITION code calculates source term groups and a frequency-weighted mean source term is determined for each group. See "PARTITION CODE" and "KEYWORD FILE" in Figure A-1c.

   (a) Dose and health effect weights are determined from separate MACCS calculations using site specific data and Iodine and other radionuclide inventories. See "DOSE & WEIGHT FACTORS" in Figure A-1c. A listing of the input file to PARTITION is provided in Appendix B of each plant volume.

   (b) The output consists of: (1) a list of the source term groups and the characteristics of the mean source term used to represent the group and (2) a file of pointers that associates with each group all the accident progression bins forming the group. See "PARTITION SOURCE TERM DATA," and "PARTITION POINTERS," respectively in Figure A-1c.

A.6   Consequence Analysis

Using the mean source term for each source term group, the various consequences were calculated with the MACCS code.[13-15] The uncertainty in the consequence parameters was not evaluated in this analysis due to resource limitations. However, weather variability was evaluated. First, base case MACCS atmospheric and early input data are modified to be specific to each source term group. The MACCS code then calculates consequence measures for each source term group and outputs the results in separate files. Selected portions of this output, as specified by the user, are then extracted from the individual source term files and combined into one file for use later in the analysis. Consequence CCDFs and mean results conditional on source term group are then generated. User specified mean MACCS results for each source term group are then extracted and combined into one file for use later in the analysis.

The calculation was performed in the following manner:

(1)   The STER code sets up unique atmospheric and early input MACCS data files for each source term group. Base case MACCS atmospheric and early input files are modified as appropriate for each source term group. See "STER CODE," "ATMOSPH. DATA," and "EARLY EFF.DAT" in Figure A-1c.

      (a)   The output consists of two files for each source term group: (1) an Atmospheric Input Per Source Term Group file and (2) an Early Fatality Input Per Source Term Group file.

(2)   The MACCS code calculates the consequences to be expected from each source term group.

      (a)   Information related to the chronic effects, dose conversion factors, site specific population data and evacuation assumptions, and meteorological data are used in addition to the source term information. See "CHRONIC INPUT," DOSE CONV.," "SITE DATA," and "METEOROL. DAT" in Figure A-1c.

      (b)   Binary files containing the consequence output for each cohort group for early health effects and for chronic health effects are created. See "EARLY 1 BINARY," "EARLY 2 BINARY," "EARLY 3 BINARY," and "CHRONIC BINARY" in Figure A-1c.

      (c)   A series of files, one file for each source term group, containing the mean consequence results are created. See "MACCS.OUT LIST OUTPUT" in Figure A-1c.

(3)   The SAVE code extracts the user specified MACCS results for each source term group and all meteorological trials and combines them into one file. See "SAVE CODE," "USER INPUT," and "SAVE.BIN" in Figures A-1c and A-1d.

(4)   The POST code generates the consequence CCDFs and mean results conditional on a source term group. See "POST CODE", "CONSEQUENCE

CCDFs POST.CCDF" and "CONSEQUENCE MEAN RESULTS POST.OUT" in Figure A-1d.

(5)   The STRIP code extracts the user specified mean MACCS results for each source term group and combines them into one file. Tables of mean consequence results are contained in XXRES2C.OUT. The same mean results, except in a different format, are also contained in XXCON2C.OUT. This latter file is processed by the risk integration code PRAMIS. See "STRIP CODE" and "USER INPUT" in Figure A-1d and "COMB. MEAN RESULTS XXRES2C.OUT" and "COMBINATION FILE XXCON2C.OUT" in Figure A-1d.

A.7   Risk Integration

The PRAMIS code[16] performs the integrated risk calculation for the mean results and calculates the contribution to risk from the following quantities: PDSs, accident progression bin characteristics, and source term groups. It also combines the LHS sample with the risk results; this information is then used as input to the regression analyses.

The calculation was performed in the following manner:

(1)   The PRAMIS code performs the integrated risk calculation for the mean results. See "PRAMIS" and "KEYWORD FILE" in Figure A-1d.

(a)   PRAMIS combines the PDS frequencies, the accident progression bin probabilities conditional on the PDSs, and the consequences to form an estimate of mean risk and its uncertainty. See "GENERALIZED RISK RESULTS" in Figure A-1d.

(b)   PRAMIS forms a file relating each LHS variable by sample observation to its consequence values. This information can then be processed by regression analysis codes or other statistical codes such as the SAS statistical package.[17] See "REGRESSION INPUT FILE" in Figure A-1d.

(2)   The PRPOST code combines the LHS sample with the full consequence results to calculate the risk CCDFs. See "PRPOST CODE," "KEYWORD FILE," and "RISK CCDFs" in Figure A-1d.

A.8 References

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APPENDIX B

RISQUE CODE DESCRIPTION

Walt Murfin

B.0   RISQUE CODE

The code RISQUE calculates the risk for each member of a Latin Hypercube sample and orders and analyzes the results. It was used in the first draft of NUREG-1150 and was also used as an analysis tool in this study while the PRAMIS code was being developed. However, the final risk calculations presented in the plant volumes of this report[1-5] were performed with the PRAMIS code.[6] While the RISQUE code was not used in the final risk calculations, it is documented in this appendix for the sake of completeness.

A description of the RISQUE code is presented in Section B.1 and a listing of the code can be found in Section B.2. While RISQUE has a number of options that allows it to calculate the costs of meltdown accidents, analyze the risk and risk reduction for preventive or mitigative safety options, analyze the cost and benefits from applying safety options, and perform statistical test on the results, these options were not used in this study and are not discussed in Section B.1.

B.1   Description of the RISQUE Code

B.1.1   Purpose of Code

The risk code---"RISQUE": Risk Integration, Sensitivity, and Quantitative Uncertainty Evaluation---calculates the risk for each member of a Latin Hypercube sample and orders and analyzes the results. Sample members for the present study were selected by the Latin Hypercube method of Iman, et al.[7] However, the code is not restricted to any particular method of sample selection. The data required are sequence frequencies, containment failure probabilities, and mean consequences, all of which must be calculated elsewhere. The risk code stands at the end of the computation chain, and the output is the final product of the plant analysis.

The code has been written specifically for DEC VAX computers, and may not run on other machines. The user should be warned that changing the values of parameters can lead to difficulties.

In the following code description, reference is made to cumulative probability distributions, percentiles, and means. It is important to remember that these terms emphatically do not refer to the distribution of risk, but only to the distribution of the sample. One should not assume that the sample in any way represents the actual or expected distribution of risk.

B.1.2   Calculation of Risk

The annual core damage frequency for sample member m is:

$$FMD = f_i(m)$$

where $f_i(m)$ is the frequency of sequence i for sample member m. Core damage frequencies are sorted in ascending order, and the 5th-, 50th-, and 95th-percentiles, mean and variance are calculated. In the calculation of percentiles, it is assumed that the frequency of each sample member is uniformly

B.1

distributed over an interval, so that the cumulative probability of the lowest sample member is 1/2N, of the second is 3/2N, or of any sample member m is (2m-1)/2N. If the sample is small, the 5th- and 95th-percentiles could fall outside of the sample. In this case, a log-normal distribution is fitted to the end points of the sample, and the appropriate percentiles of the log normal distribution are found. This extrapolation was not required for any of the samples used in the SARRP study.

The risk, in consequence measure c, for sample member m is:

$$r = \{S\}[P][B][Q]\{C\}$$

where:

{S}   is a 1 x n (number of sequences) row, whose members S represent the frequency of sequence i for sample member m. {S} is different for each sample member.

[P]   is an n x n (number of plant damage states) matrix whose members P are the pointers from sequence i to plant damage state j, 1 if the sequence is a member of the plant damage state, and 0 otherwise. This matrix does not vary from one sample member to another.

[B]   is an n x n (number of bins) matrix, whose members B represent the probability of a source term bin k given plant damage state j. This matrix is different for each sample member.

[Q]   is an n x n (number of release clusters or source term groups) matrix, whose members Q represent the probability of bin k selecting cluster l, 1 if the cluster is selected and 0 if not. This matrix is different for each sample member. Note, the term cluster and source term group refer to the same quantity.

{C}   is a column vector of length n whose members C are the mean consequence in consequence measure c for cluster l. This vector is different for each sample member if consequence issues are to be considered, but otherwise is the same for all sample members. Note also that mean consequences are used; weather data are not considered except in the average.

The risks are sorted, and the 5th-, 50th-, and 95th-percentiles, mean and variance are calculated. The logarithmic midpoint of all sample members having risk greater than zero is found, and the number of sample members above and below the midpoint is counted.

The calculation of risk entails a very large number of sample multiplications and additions, which are repeated for each consequence measure and sample member. By far the greatest part of the code is devoted to the analysis of results, rather than to the simple calculation of risk outlined above.

B.1.2.1   Analysis of Contributions to Risk

The code computes the fraction of risk attributable to each frequency, each
source term bin, and each consequence cluster. For example, the fraction of risk
attributable to sequence s is:

$$f\ (s) = r\ (s)/R$$

where:

r(s)   is the risk for sample member i attributable to sequence s,
R   is the total risk for sample member i.

B.1.2.2   Detailed Analysis of Individual Sample Members

As an option, a detailed analysis of a selected group of sample members can be
carried out. For each sample member selected, for each sequence, the risk
attributable to each source term bin as well as the consequence cluster selected
for that bin is shown. Also, the fractions of risk for each sequence, bin, and
cluster are given. The selection of sample members for detailed analysis is
completely arbitrary.

B.1.3   Structure of Code

LIST OF SUBROUTINES IN RISQUE

RISQUE: Main routine; controls the flow to some subroutines, and initializes
           and resets baseline variables.

REDATA: Reads input data.   See Section B.1.4 for description of data
           requirements.

POINT: Calculates and accumulates risk.

OUTRISK: Output of risk. Sets up and selects data for regression.

PCTILE: Calculates percentiles of an ordered array.

NORMINV: The inverse normal distribution; given Q(z), determine z.

ONSITCOS: Calculates average discounted onsite cost.

SORT: Sorts a one-dimensional array in ascending order. A subsidiary
           array (probability, sample number, or dummy) is carried along.

OUTCOST: Calculates and outputs annual average costs of meltdown accidents.

FRESID: Controls solution of regression equations, calculates residuals and
           F ratio.

B.3

SOLVE: Solves a system of simultaneous linear equations by the method of Gaussian Elimination.

SIGNIF: Calculates percentage points of the F distribution.

STUDENTS: Calculates percentage points of the Student's-t distribution.

FACT: Calculates a ratio of factorials used in SIGNIF.

RISKRED: Calculates and outputs differential risk and risk ratio.

COSTBEN: Calculates and outputs costs and benefits of safety options.

RETEMAC: Reads the TEMAC frequency file.

RECODES: Reads names of source term bins.

REDEVNT: Reads event tree output file.

REDPOINT: Reads file of pointers from source term bins to clusters.

REDCONS: Reads the file of mean consequences.

FCHISQ: Calculates the value of chi-squared.

QCHISQ: Calculates percentage points of the chi-squared distribution.

DETANAL: Detailed analysis of selected sample members.

CCDF: Calculates complementary cumulative distribution functions of risk for each sample member.

B.1.4   Input Data Requirements

Two versions of the code can be used; the versions differ only in input data requirements. In one version, all input data are included in a single data stream. In the other version, separate files are called for from the main data stream; the separate files contain much of the detailed data. The second version was used in the NUREG-1150 study and is the version described below. Because many of the options available in the code were not used, "dummy" input data was used for variables related to these options. Dummy input data was used for Record numbers 7 through 11A and 24 through 30.

Note that most of the data will be entered in "free" format. The few exceptions are noted below.

Record Number	Format (if not free)	Description
1	---	NUMBAS = Number of base cases to be run.
2	A80	NAMBAS = Name of base case
3	A80	HDR_WORDS = Identifying or descriptive text.
4	---	NUMALT, NUMSAMP, NUMCFG, NUMCFM, NUMREL, NUMCSQ
		NUMALT = Number of safety options to be run (max. = 21)
		NUMSAMP = Sample size (max. = 150)
		NUMCFG = Number of plant damage states (max. = 15)
		NUMCFM = Number of source term bins or containment failure modes (max. = 100)
		NUMREL = Number of consequence clusters (max. = 45)
		NUMCSQ = Number of consequence measures (max. = 6)
5	---	KCOS, KDOS, KFAT, KILL, KLAT
		KCOS = Index of consequence measure for property damage.
		KDOS = Index of consequence measure for population dose.
		KFAT = Index of consequence measure for early fatality.

Record Number	Format (if not free)	Description

KILL = Index of consequence measure for early illness.

KLAT = Index of consequence measure for latent cancer fatalities.

6	20L1	(IOPT(J),J=1,13)

If IOPT(1)=.TRUE.; risk is conditional on core melt, otherwise, risk is absolute risk per year.

If IOPT(2)=.TRUE.; a limited set of sequences will be used, otherwise, all sequences will be used.

If IOPT(3)=.TRUE.; the base case risk will be printed.

If IOPT(4)=.TRUE.; safety option risk will be printed.

If IOPT(5)=.TRUE.; safety option differential risk will be printed.

If IOPT(6)=.TRUE.; safety option risk ratio will be printed.

If IOPT(7)=.TRUE.; output for STEP will be written on file STEPOUT.DAT

If IOPT(8)=.TRUE.; a chi-squared test of base case risk will be performed.

If IOPT(9)=.TRUE.; a detailed analysis of selected sample members will be written out.

If IOPT(10)=.TRUE.; CCDFs will be calculated for each sample member. See section 5.2.3.6 for input data required for CCDFs.

If IOPT(11)=.TRUE.; Probability sums will be normalized to one.

If IOPT(12)=.TRUE.; Probability sums out of tolerance will abort the run.

If IOPT(13)=.TRUE.; Bin not in bin list will abort the run.

Record Number	Format (if not free)	Description

6A   ---   (Only if IOPT(9)=.TRUE.)

                         NUMSEL=Number of sample members for detailed analysis.

6B   ---   (only if IOPT(9)=.TRUE.)

                         (ISEL(JSEL),JSEL=1,NUMSEL)
ISEL=ranking (from bottom) of sample members selected for detailed analysis.

7   ---   NUMISSGP=number of issue groups

8,   A80   (NAMISSGP(ISSGP),ISSGP=1,NUMISSGP)

                         Names of issue groups. This record is repeated NUMISSGP times.

9   ---   NUMISS(ISSGP),(NUMLVL(ISS,ISSGP),ISS=1,NUMISS(ISSGP))

                         NUMISS=Number of issues in this issue group.

                         NUMLVL=Number of levels for this issue.

10   A80   NAMISS(ISS,ISSGP)=Name of issue.   Repeat record 10 NUMISS times.

11   10L1   (NOMINAL(ISS,ISSGP),ISS=1,NUMISS(ISSGP))

                         If NOMINAL=.TRUE.; this is a nominal or categorical variable.

                         If NOMINAL=.FALSE.;this is a ratio or interval variable.

11A   ---   (For each issue for which NOMINAL is .FALSE.)

                         (SLVL(ISS,ISSGP,LEVEL),LEVEL=1,NUMLVL(ISS,ISSGP))

                         SLVL=physical quantity corresponding to this level.

(Repeat records 9 through 11 or 11A NUMISSGP times)

12   ---   VECTFIL=Name of file from which sample is to be read.

Record Number	Format (if not free)	Description
13	---	NUMSEQ=Number of sequences (max. = 20).
14	---	NAMSEQ(ISEQ),ICFGS(ISEQ)
		NAMSEQ(ISEQ)=Name of sequence ISEQ
		ICFGS(ISEQ)=Index of plant damage state to which sequence belongs (Repeat record 14 NUMSEQ times).
15	---	TEMFIL=Name of TEMAC file from which sequence frequencies will be read.
16	20L1	(Only if IOPT(2)=.TRUE.)
		(IUSE(ISEQ),ISEQ=1,NUMSEQ)
		IUSE=.TRUE.; this sequence will be used, otherwise this sequence will be bypassed.
17	---	CODEFIL = Name of file from which source term bin names ("codes") will be read.
18	---	CFGFIL = Name of file from which source term bin (containment failure mode) probabilities will be read. (Repeat record 18 NUMCFG times)
19	---	POINTFIL = Name of file from which pointers from source term bins to consequence clusters will be read.
20	---	NUMCSQVECT = Number of consequence vectors to be read in. This will be one if there are no consequence issues. NUMSEQVECT is the number of unique combinations of consequence issues if consequences are varied, and a coding change will be required in Subroutine REDCONS.
21	A80	CONS_WORDS = Descriptive information about consequences.
22	A80	(NAMCSQ(ICSQ),ICSQ=1,NUMCSQ) = Name of consequence measure. (Repeat record 22 NUMCSQ times).

Record Number	Format (if not free)	Description

```
------+-------+--------------------------------------------------
```

23   ---   CONSFIL = Name of file from which consequences will be read.

24   ---   JBLT,JUSLIF,JPRES (Note: all integer)

                         JBLT = Calendar year in which plant was built.

                         JUSLIF = Estimated useful life at time on-stream.

                         JPRES = Present calendar year.

25   ---   PMWE,CAPF,DISCR,ESCR

                         PMWE = Plant power, MWe.

                         CAPF = Average capacity factor, percent.

                         DISCR = Average capital discount rate.

                         ESCR = Average fossil fuel escalation rate.

26   ---   (PPCI(I),I=1,3) = Low, middle, and high power cost differential.

27   ---   (CPKWI(I),I=1,3) = Low, middle, and high cost per kilowatt installed.

28   ---   (CCUP(I),I=1,3) = Low, middle, and high costs of cleanup after core damage accidents.

29   ---   (CDEC(I),I=1,3) = Low, middle, and high costs of decommissioning.

30   ---   (OSHC(I),I=1,3) = Low, middle, and high onsite health costs due to core damage accidents.

B.1.5 Output Data

Input data are not, in general, written out; the reason is that output is quite voluminous even without repeating the input. If the user needs to refer to the input data, a printout of the input files is suggested. The sample member levels are printed out--by issues--so that the user will have an ordered input sample to refer to.

B.1.5.1 Base Case Data

There will be no printout of base case data, except for cost data, unless input option 3 is selected. If the base case is to be printed out the first segment of output data will be the distribution of core damage frequency.

For each consequence measure, the following are printed out:

(1)   Cumulative probability distribution of risk.

(2)   Issue levels for each sample member, ordered by increasing risk.

(3)   Fractional contribution of each sequence to risk.

(4)   Fractional contribution of each source term bin to risk.

(5)   Fractional contribution of each release (consequence cluster) to risk.

(6)   Results of one-at-a-time rank regression.

(7)   If input option 8 is selected, results of chi-squared analysis.

If input option 9 is selected, the detailed analysis of selected sample members follows. The following is printed out for each consequence measure:

(1)   Ranking of selected sample member.

(2)   Issue levels for sample member.

(3)   For each sequence, the bins whose contribution to that sequence is at least 1%, the consequence cluster selected for the bin, the mean consequence for the cluster, and the contribution of the bin to risk for the sequence. Following the individual sequence information, the fractional contributions of each sequence, bin and cluster are given. The output for the detailed analysis of selected sample members is quite voluminous, and judgment should be exercised to avoid being inundated by output.

The last set of output data is the annual costs of meltdown accidents. For each component of cost, the code prints out the mean and 5th-, 50th-, and 95th-percentiles of cost.

B.1.6 Listing of Typical Data Files (Version 2--RISQUE_2)

Explanatory text enclosed in brackets does not appear on the input file.

B.1.6.1 Listing of File INFILE.DAT

```
1                                          [File begins here]
SPECIAL PLANT LLH
CONSEQUENCES BY MACCS, SEQ. BY TEMAC, ST BY SPSOR
0  150  5  93  24  6                       [No safety options]
6  5  1  2  4
FFTFFFFTTF                                 [Base case risk, chi-sq., and
                                           details printed]
20
1 2 3 4 5 6 7 8 9 10 141 142 143 144 145 146 147 148 149 150
                                           [Details of lowest and highest
                                           10]
4
FRONT END ISSUES                           [Names of issue groups]
CET ISSUES
ST ISSUES
CONS ISSUES
5  4  4  4  4  2
SLC FAILURE TO ACTUATE                     [Names of front end issues]
STUCK OPEN SRV VAC BRKR
DUMMY ISSUE
FAILURE TO VENT
SW MOD A VS. MOD B
TTTTT
16 2 4 4 2 2 6 8 4 5 3 5 5 4 3 4 3
SIZE OF SP BYPASS                          [Names of CET issues]
CONT FAIL PRESS (T<500)
CONT FAIL PRESS (800-1200F)
SIZE CONT FAIL RAPID
SIZE CONT FAIL SLOW
VB MODE FOR HI-P FLOW MELT
DUMMY ISSUE
CONT PR BEF VB (LONG-TERM TB)
PRESS RISE @ VB
DELTA-P INTERACTION
DRY DW MT
WET DW MT
DW MT W/ HP MELT EJ
H2 BURNS IN RB
DW SPRAY
DUMMY ISSUE
TTTTTTTTTT
TTTTTT
12 4 4 5 5 5 4 4 4 4 4 5 6
IN-VES RELEASE                             [Names of source term issues]
CSI DECOMP
IN-VES REL LEAKED
```

```
S POOL DF
S POOL DF, VOL I
REVOL AFTER VB
CCI REL
RB DF
REF BAY DF
LATE IODINE
DUMMY ISSUE
DUMMY ISSUE
TTTTTTTTTT
TT
1 2
DUMMY ISSUE
T
'SPVECTOR.DAT'                          [Sample file]
5
'TB' 1                                  [Sequences--for this run,
'TBUX' 2                                sequences and plant damage
'TBU' 3                                 states are identical]
'TCSX' 4
'TCSRX2' 5
'SPSEQFREQ.RIS'                         [TEMAC file]
'SPBIN.KEP'                             ["Codes"]
'SPTBR.RIS'                             [Bin probability files]
'SPTBUXR.RIS'
'SPTBUR.RIS'
'SPTCSXR.RIS'
'SPTCSRX2R.RIS'
'SPFINAL.CLS'                           [Cluster file]
1
CONSEQUENCES BY MACCS 9/01/85
EARLY FATALITIES
EARLY ILLNESS
IND. RISK OF FATALITY
LATENT CANCERS
POP. DOSE 50 MI.
PROPERTY DAMAGE
'MACCS_SPEC.OUT'                        [Consequence file]
  1974  40    1985                      [Cost data]
  1065. 65.    .04   .06
  1.9E+5  2.2E+5  3.0E+5
  1500.  3000.  4500.
  8.E+8  1.7E+9   2.5E+9
  1.E+8  1.E+8  1.E+8
  0.  .65E+7  1.3E+7                     [End of INFILE.DAT]
```

```
2 3 3 2 1 2 3 3 2 2 4 8 2 2 2 2 4 3 3 2 3 1 2 3 2 4 3
1 3 1 3 1 3 1 4 1 4 3 2 2 4 3 2 1 4 1 3 3 2 5 3 1 2 3
2 2 3 1 4 4 3 4 1 3 3 5 2 2 1 3 3 3 2 1 3 2 2 2 2 3 2
2 3 5 4 4 3 2 2 3 3 2 3 4 3 3 2 3 3 1 2 1 2 3 4 3 1 2
2 4 2 2 3 5 3 2 2 1 2 3 3 3 3 3 2 2 2 4 2 1 1 3 2 5
1 3 3 3 3 2 1 3 2 2 1 1 1 3 1 1 5 2 4 3 2 3 3 2 4 2 2
3 1 3 4 2 4 5 2 2 3 1 3 1 2 3 2 2 2 2 8 3 2 2 2 1 3 3
3 3 2 2 4 3 3 3 2 3 4 4 5 3 1 3 2 2 3 1 1 4 3 2 1 2
8 2 4 1 2 5 3 1 1 1 2 3 2 2 3 3 2 2 3 3 5 3 1 2 2 2
2 1 2 4 2 2 2 2 3 2 5 2 5 5 3 3 3 3 2 3 2 2 3 3 2 2 4
3 5 1 2 3 2 4 2 2 1 2 2 2 1 2 1 2 5 2 4 3 1 3 2 2 1
4 3 4 3 3 3 1 3 3 5 4 2 4 1 2 3 2 1 3 3 2 1 2 4 2 4
2 1 1 1 3 2 1 1 3 4 2 5 4 3 2 3 3 1 3 1 2 2 2 1 2 1
3 3 2 2 6 8 2 3 2 2 2 4 2 3 3 2 2 3 2 2 3 2 3 4 2 3 6
1 2 3 2 4 2 1 3 3 1 2 2 2 2 2 2 5 2 3 1 3 3 2 2 4 1
3 3 3 2 3 2 4 2 2 2 2 1 1 2 1 3 2 2 1 4 6 3 5 2 5 5
4 2 4 2 2 4 2 3 5 3 2 2 4 3 2 5 1 4 2 2 4 2 1 3 2 2
1 3 8 1 1 1 4 1 1 2 3 3 2 3 2 4 2 4 2 4 3 2 5 2 2 2
3 3 2 2 1 4 3 2 1 2 6 3 4 1 3 1 4 2 3 3 4 2 4 3 3 2 2
3 4 2 1 3 2 2 4 3 3 1 1 3 2 2 2 5 4 2 3 2 3 4 4 3 3
3 2 1 1 4 3 4 2 3 3 3 4 1 2 3 2 3 2 1 1 4 2 2 2 1 1
1 3 1 5 1 3 3 2 3 1 4 4 2 2 2 3 3 3 4 3 6 1 3 3 2 3
2 1 3 3 2 1 4 7 2 1 1 5 5 4 3 4 2 3 3 4 2 3 3 2 1 3 2
3 4 2 3 3 3 2 1 1 3 2 1 2 2 1 2 3 2 5 2 4 3 3 2 1 3
3 5 3 3 2 2 3 2 2 4 1 2 2 3 2 2 1 4 2 2 1 3 8 2 3 2
5 4 4 3 3 2 2 2 4 2 4 2 3 1 2 4 5 3 2 4 3 2 3 1 1 4
3 2 1 5 2 2 4 2 5 4 4 2 2 2 2 3 2 2 2 3 3 3 3 4 1 1
2 2 3 3 2 1 3 1 2 2 4 6 3 1 1 5 2 1 3 3 3 3 3 4 2 5
3 1 1 4 3 2 4 1 2 2 2 2 1 1 4 2 2 2 2 4 2 2 2 4 1 3
2 2 2 3 2 2 3 4 2 1 3 4 3 1 2 2 1 2 3 4 2 2 4 3 2 2
2 8 3 1 3 5 5 4 3 2 1 1 2 2 2 2 3 2 3 3 3 3 3 2 2 2
3 2 2 1 3 2 2 2 5 4 3 5 1 4 1 4 3 2 1 2 2 2 2 4 3 2 3
4 3 5 2 1 3 2 2 3 2 1 4 3 2 1 2 2 2 2 3 4 4 3 2 4 2
3 1 2 3 3 4 3 3 2 4 1 4 2 4 4 2 3 1 1 2 4 2 2 5 3 2
2 2 1 3 4 1 3' 2 2 2 4 3 3 3 2 2 4 3 4 2 2 4 3 2 2 1
2 4 2 2 2 4 1 2 1 1 5 4 4 3 2 3 2 2 2 3 2 3 3 3 3 2 1
1 2 3 1 2 2 1 1 3 3 2 1 4 7 2 3 1 2 1 4 3 1 1 2 4 2
2 4 4 3 3 4 2 2 2 2 3 2 3 3 1 1 3 2 2 2 4 6 1 4 1 2
5 4 3 3 3 3 2 2 2 4 3 3 2 4 4 2 4 2 2 4 3 2 1 1 2 2
2 1 2 7 3 2 1 1 5 1 3 3 2 1 2 4 2 2 2 4 4 4 3 3 5 2
2 3 2 3 1 1 4 3 2 2 2 5 3 2 2 2 3 4 2 2 1 1 1 4 2 3 4
3 3 4 3 1 6 2 2 2 3 4 1 2 3 1 2 2 4 4 3 2 2 3 1 2 1
3 2 2 3 2 2 5 3 2 3 3 3 4 6 1 3 3 3 3 2 1 3 3 2 2 5
3 2 2 2 2 2 3 1 4 3 2 3 3 3 4 2 2 2 3 4 3 6 1 3 2 1
3 1 1 2 2 2 2 2 3 2 1 5 5 4 3 2 1 1 2 1 2 4 3 3 3 3
2 3 3 2 3 2 1 3 1 1 3 2 2 2 2 2 2 1 1 3 3 4 2 2 2 2
4 3 2 3 2 2 1 2 4 5 4 1 1 2 2 3 1 1 2 3 1 1 5 5 3 2
1 5 1 4 2 1 2 2 3 2 4 4 4 1 2 3 3 5 2 1 1 2 2 2 1 1
4 3 2 1 4 4 2 3 1 5 5 1 2 3 1 3 2 1 2 4 3 2 2 4 2 5 1
2 3 3 3 2 1 1 4 2 2 2 2 5 2 1 1 5 5 2 3 2 1 3 3 4 2
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3 2 2 3 3 3 3 4 2   3 2 4 4 2 1 4 3 2 1 2 8 2 2 3 5 5
3 3 2 2 1 3 4 2 3 3 4 3 4 2 4 2 1   4 2 3 1 1 1 3 2 2
2 4 2 3 2 2 4 1 3 1 4 3 1 2 3 4 3 3 3 3 1 3 1 2 1   2
3 3 2 1 1 4 3 2 1 3 3 2 3 1 5 1 3 2 2 3 3 3 2 2 3 2 2
2 1 3 2 2 2   2 3 2 2 2 1 4 3 2 2 4 4 2 3 2 5 4 4 1 1
3 1 2 4 3 3 3 2 4 1 3 2 5 1   3 3 3 4 2 1 3 2 2 2 3 4
1 2 2 5 2 4 1 3 2 2 2 1 2 5 3 3 3 4 4 3 3 1   2 1 3 2
1 1 3 3 2 1 2 3 2 5 2 2 5 4 3 4 2 2 3 2 2 4 2 1 2 2 2
1 1 1   2 2 4 4 1 1 3 3 2 2 6 2 3 1 1 5 2 4 2 2 3 2 2
4 3 5 4 3 2 2 2 2 2 1   1 3 4 2 1 1 2 3 1 1 1 7 3 2 2
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2 2 1 4 7 3 1 2 3 4 2 2 2 1 3 1 5 3 4 3 2 3 2 2 4 5 2
 1 3 3 2 2 1 3 3 2 2 4 8 3 1 1 5 4 3 1 3 1 2 3 2 3 4
3 3 2 3 2 4 4 2   3 3 2 2 1 1 3 2 2 1 4 8 3 1 1 3 5 2
2 2 3 1 2 2 3 3 3 3 2 3 2 2 5 1   3 4 2 2 2 2 3 3 2 1
6 2 3 2 3 5 5 3 1 2 2 2 2 3 2 3 2 2 2 4 2 4 1 2   3 4
3 3 1 1 4 3 2 1 5 1 2 4 2 1 4 3 2 2 1 2 1 3 4 4 2 2 3
4 3 2 1 1   2 1 2 2 1 1 4 3 2 2 5 5 2 .1 1 5 4 4 2 3 2
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1 2 4 1 3 3 3 3 2 1 5 2 3 3 4 1 2 3 3 1 2   3 3 2 3 2
1 2 2 2 1 4 2 2 5 2 5 5 3 2 2 2 2 1 5 2 4 3 2 2 2 3 1
3 1   3 3 3 2 1 1 3 2 2 1 5 8 2 2 2 5 5 1 2 2 3 1 2 2
1 2 4 2 1 4 4 5 4 1   3 1 2 3 1 1 2 3 2 2 4 2 2 4 1 2
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2 3 2 1 2 2 3·2 2 2 3 3 3 4 1 5 4 2 1 2 1 1 2 2 3 4 3
1 2 2 3 4 1 2   4 4 1 3 2 1 2 3 1 2 1 8 3 4 2 5 4 3 3
3 1 2 1 4 2 5 2 3 2 3 3 5 6 1   3 4 2 3 1 1 3 2 2 1 2
8 2 3 1 3 1 3 1 2 1 1 2 2 2 3 2 1 2 3 3 1 1 2   3 4 3
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4 4 4 5 2 3 2 4 3 4 5 1   3 2 3 3 2 1 3 2 1 2 6 7 1 2
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2 1 4 3 2 2 6 5 2 3 2 5 1 3 3 2 1 2 2 4 4 3 1 3 4 1 2
1 3 2   2 1 3 2 2 2 4 4 2 2 1 6 1 2 1 5 3 4 2 4 2 1 1
3 1 2 2 2 3 3 2 4 6 1   1 3 2 2 2 1 2 3 2 1 1 2 3 2 3
5 3 4 3 3 3 2 2 1 2 3 3 3 3 3 3 2 6 2   2 2 3 3 2 1 4
3 2 1 3 6 3 3 3 4 5 2 3 2 2 3 1 3 2 4 3 2 3 4 5 5 2
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4 3 2 3 3 2 6 2   2 2 3 3 1 1 4 2 2 1 2 1 2 1 2 4 3 4
2 3 1 2 3 3 2 4 4 2 3 2 3 4 2 1   3 2 2 2 1 1 4 2 2 1
4 5 2 3 3 5 1 4 3 2 3 1 3 3 1 3 2 3 3 3 3 1 3 5 2   3 1
2 4 2 1 2 2 2 1 3 7 2 2 2 5 3 2 1 1 2 2 2 2 3 3 2 3 2
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2   2   1   6   1       2   3   3   2   1   2   3   3   2   1   1   6   3   2   2   4   4   4   2   3   2
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1   2   3   2   2   5   2   2   3   3   1   5   4   2   3   3   2   1   3   3   3   2   2   2   3   1   1
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3   4   1   3   1   1   4   2   2   2   2   7   2   2   1   4   1   3   3   2   3   1   2   3       2   4   4
2   2   2   1   4   4   2       4   2   2   3   1       1   3   3   2   1   3   1   1   1   2   3   4   2   3
3   1   2   1   2   2   4   3   1   2   4   3   1   2   1       3   2   2   1   1   1   2   3   2   1   4
4   2   1   3   2   2   4   3   2       2   3   3   2   3   3   2   3       3   2   3   3   3   2       2   3   3
3   1   1   4   3   2   2   1   7   1   5   2   3   1   4   1   2   1   2   3   4   2   5   2   3   2   4
2   3   1   1       3   3   4   2   2   1   4   3   2   2   4   5   2   2   3   3   1   1   3   1   1   2
3   2   2   2   4   3   2   4   3   5   2   1       3   1   3   1   2   1   4   2   2   2   3   5   2   5
1   5   4   4   3   3   3   2   1   2   2   2   2   2   3   4   3   2   1   1       2   2   3   3   2   1
3   2   2   2   4   7   3   2   1   3   4   1   3   1   2   3   4   4   1   4   3       3   4   3   2   2   1
2       3   2   3   3   1   1   3   1   2   2   4   2   3   2   3   2   1   3   3   2   1   1   1   3   2
4   2   3   1   4   2   3   5   2       2   3   3   3   2   2   3   1   2   1   6   4   3   3   1.   1   4
4   2   3   1   2   3   3   2   4   3   3   3   2   4   3   5   1       2   2   3   3   1   1   4   1   1
1   4   4   3   1   2   1   1   4   1   4   1   2   1   4   2   2   1   3   2   2   2   5   1   1       2
2   3   2   1   1   3   2   2   2   3   2   3   4   1   5   5   1   2   3   2   1   3   2   3   3   2
3   1   3   3   2   1       3   2   1   1   2   1   2   3   2   1   4   4   3   1   2   5   5   2   3   2
2   1   3   3   4   3   3   4   2   3   2   2   1   1       3   3.4   3   1   1   3   3   2   1   6   3
2   3   2   5   4   4   3   3   3   3   2   4   4   4   4   4   3   3   2   4   6   2       2   3   1   3
2   1   2   2   2   2   4   3   2   5   2   5   2   4   3   3   1   2   2   2   3   3   3   2   4   2   2
3   1   2       3   2   3   1   1   1   2   3   2   1   2   7   3   3   1   5   5   4   2   2   1   2   2
2   4   4   3   4   2   2   3   3   4   1       2   1   3   2   2   2   2   2   2   2   1   7   4   3   2
5   2   4   1   2   3       2   2   3   1   1   3   2   2   3   2   3   2   1   2   4   3   2   1   2   1   3
2   2   2   3   5   2       3   1   5   5   4   2   1   2   3   3       2   2   4   2   3   2   2   4   4   6   2
    1   2   2   3   2   1   3   3   2   1   3   5   2   1   2   5   4   1   1   2   2   1   3   3   4   2
2   1   3   4   3   5   4   2       3   3   1   2   1   1   4   2   2       2   1   3   2   1   2   5   1   3
2   2   3   3   2   5   2   3   3   2   2   3   3   3   1   1       3   3   2   3   1   1   3   2   2   1
3   1   2   4   1   5   4   3   1   1   3   2   1   2   3   4   3   3   4   2   3   5   6   2       3   3
4   1   1   1   3   3   2   2   1   8   2   3   1   5   1   2   2   3   2   3   2   4   4   4   3   3   4
4   4   2   2   2       3   3   2   3   2   1   2   2   2   1   2   6   1   5   1   5   ·1   4   2   3   2
2   2   2   3   4   2   3   3   3   3   5   3   1       2   2   3   4   2   1   4   3   2   1   1   1   3
1   1   1   2   4   2   2   1   2   1   2   2   3   3   2   2   4   4   1   2   1       2   2   2   3   2
1   2   3   2   1   2   1   2   4   2   5   1   4   2   1   1   2   2   4   1   4   4   1   3   4   3   3
6   1       1   2   1   3   1   1   3   2   2   1   2   3   1   2   1   1   3   4   3   1   3   2   2   2
5   3   3   2   1   4   2   3   5   1       1   3   3   3   2   1   4   2   1   2   6   2   3   1   2   4
4   3   2   3   2   1   3   2   1   4       2   3   2   2   4   1   6   1       3   2   4   2   1   1   2   3
2   2   2   7   2   3   2   4   3   4   2   2   3   2   2   2   3   5   3   2   3   3   3   5   2   1
2   3   2   3   1   1   4   3   2   2   4   4   4   2   1   5   4   1   2   3   1   1   3   3   4   2   2
4   1   3   4   1   3   2       1   3   1   1   2   1   2   3   2   1   4   6   2   1   1   1   2   3   1
1   3   3   2   1   2   3   1   3   3   3   2   4   4   2       2   2   2   4   1   1   4   2   2   1   2
5   1   3   2   5   5   3   2   4   2   3   4   5   4   3   3   3   4   1   3   5   2   2       2   3   3
2   1   1   3   2   2   2   5   6   2   2   3   5   5   1   2   3   3   2   3   2   2   5   2   3   2   4
3   2   4   2       2   2   3   4   1   1   3   2   1   1   3   8   2   4   1   3   2   3   3   1   2   3
1   3   4   3   2   3   2   2   3   1   3   1       3   2   2   2   1   1   3   2   1   2   2   1   4   5
3   5   4   2   2   3   1   4   2   2   3   2   1   2   2   3   2   5   6   1       3   4   2   2   1   1
3   1   1   2   1   3   2   1   2   5   5   4   3   2   1   1   2   4   4   4   2   2   1   2   2   3   3
```

```
1   1   2   1   3   2   1   2   3   2   1   6   1   3   2   1   2   2   4   3   2   3   3   2   3   2
2   1   4   3   4   2   4   2   2       3   2   3   3   1   1   3   3   2   1   4   2   3   4   1   2   4
4   2   3   3   2   3   5   1   3   3   2   2   3   3   3   1   2       3   4   3   4   1   1   3   2   2
1   2   3   2   4   1   1   5   3   3   3   1   2   2   3   3   2   3   2   1   4   3   4   6   2       2
3   3   1   1   1   4   2   2   1   6   5   4   5   2   5   1   4   3   3   1   3   4   2   2   2   4   3
3   4   3   2   4   1       4   3   4   3   1   1   2   2   2   1   6   7   3   3   2   5   1   4   3   3
1   3   3   2   2   2   2   1   3   4   3   4   5   1       1   2   2   2   1   1   3   2   2   1   4   4
2   3   2   5   4   2   2   4   1   2   2   5   4   2   3   1   4   3   2   3   4   2       2   2   1   3
1   2   3   3   2   1   2   6   3   3   1   5   1   4   2   2   2   3   2   3   2   2   3   2   1   4   3
1   2   1       3   3   1   1   2   1   4   2   2   1   1   4   2   2   1   3   3   1   1   2   3   2   4
3   2   3   3   4   2   4   3   3   6   1       2   3   2   2   1   1   4   3   2   2   4   3   2   4   1
4   3   3   3   3   2   2   1   2   2   4   2   3   1   3   4   2   5   2       3   3   2   2   1   2   4
2   2   1   4   5   2   3   2   5   1   3   2   3   3   1   2   1   2   5   4   4   1   3   2   1   1   2
 1   3   3   3   1   1   3   3   2   2   3   1   3   5   2   1   5   3   1   2   1   2   4   2   2   2
2   3   4   1   2   4   5   1       3   3   3   4   2   1   4   2   1   2   1   4   2   2   2   2   5   3
2   3   2   2   3   1   2   5   3   3   4   4   1   1   3   2       2   3   2   3   1   1   3   3   2   2
6   6   2   2   1   5   2   2   2   3   2   3   3   1   1   2   3   2   2   2   2   2   5   1       2   1
2   2   1   1   3   3   2   2   2   1   2   3   2   4   5   2   3   2   1   2   2   2   2   5   2   2   2
3   4   4   3   1       2   3   2   2   2   1   4   2   2   2   4   2   1   3   2   5   4   3   1   2   2
1   1   4   1   2   3   4   2   4   2   5   4   1       2   4   4   2   1   1   4   2   2   1   2   3   1
1   2   5   2   4   1   3   2   3   1   5   3   4   3   3   1   3   2   2   6   2       2   2   3   2   2
1   4   2   2   1   5   5   3   2   1   3   4   4   2   2   2   1   3   2   4   1   2   3   3   3   4   4
4   2       1   2   2   3   2   2   3   3   2   2   5   1   1   3   1   3   5   3   2   2   1   2   1   4
3   4   3   2   2   3   2   5   3   1       3   3   4   1   2   1   3   1   2   1   2   6   2   4   2   1
4   4   2   2   3   3   3   2   2   4   3   1   2   1   2   3   1   2       3   1   1   4   1   1   3   3
2   2   4   4   3   2   1   5   4   4   3   4   3   1   3   4   2   2   4   2   3   4   3   2   3   1
3   3   2   2   1   1   2   2   2   2   3   4   2   3   1   5   4   4   1   2   1   3   3   2   2   3   3
4   2   2   3   2   6   2       4   1   3   3   1   2   2   1   2   2   6   4   2   1   2   5   3   4   3
3   1   2   3   2   3   4   2   3   3   4   2   5   4   2       3   2   2   2   1   1   3   2   1   2   6
7   2   2   1   1   5   4   1   3   1   3   3   3   4   4   3   2   1   4   3   1   3   2       3   1   3
2   2   1   4   2   2   2   2   6   3   2   2   2   5   4   1   2   1   2   1   4   3   3   3   3   1   4
3   5   1   1       3   2   3   2   1   1   4   2   2   1   5   6   3   1   2   4   1   4   2   3   2   2
1   1   5   3   2   1   3   4   2   5   6   1       2   2   3   3   1   1   1   1   2   2   4   3   3   2
2   5   3   4   1   2   2   2   3   3   2   2   3   2   3   4   4   1   4   2       3   2   2   3   1   1
3   1   2   1   6   8   2   5   2   5   4   4   2   1   3   1   4   4   2   4   2   2   2   4   2   1   5
1   2   3   2   2   2   1   4   3   2   1   6   6   3   4   2   4   1   3   3   4   1   1   3   2   5
4   2   2   3   1   2   2   2   2   3   3   3   2   1   2   2   2   2   1   6   3   3   4   1   5   1
4   2   4   1   2   1   2   1   4   3   3   3   4   3   2   4   1       4   2   2   3   1   1   3   3   2
2   3   5   2   3   2   5   3   1   1   3   2   4   4   3   4   1   2   3   1   3   3   1   1   2       4
3   3   2   2   1   3   3   1   1   5   2   2   4   1   1   1   4   3   3   2   2   3   4   1   4   3   1
3   3   3   1   6   1                                          [End]
```

B.1.6.3 Listing of File 'SPBIN.KEP'

KEPT BINS: SPECIAL PLANT ACCIDENT PROGRESSION   [Start]

```
          6          93
AAAAAA
AAAAAB
AAABAA
AAACAA
AAACAB
AABAAA
AABABA
AABABB
AABBAA
AABBBA
AABCBA
AABCBB
BAAAAA
BAAAAB
BAABAA
BAACAA
BAACAB
BABAAA
BABAAB
BABABA
BABABB
BABBAA
BABBBA
BABCAA
BABCBA
BABCBB
CAAAAA
CAAAAB
CAABAA
CAACAA
ÇAACAB
CABAAA
CABABA
CABABB
CABBAA
CABBBA
CABCAA
CABCBA
CABCBB
DAAAAA
DAAAAB
DAABAA
DAABAB
DAACAA
DAACAB
DABAAA
```

```
DABAAB
DABABA
DABABB
DABBAA
DABBAB
DABBBA
DABBBB
DABCAA
DABCAB
DABCBA
DABCBB
DBBAAA
DBBAAB
DBBABA
DBBABB
DBBBAA
DBBBAB
DBBBBA
DBBBBB
DBBCAA
DBBCAB
DBBCBA
DBBCBB
EAAAAA
EAAAAB
EAACAA
EAACAB
EABAAA
EABAAB
EABABA
EABABB
EABCAA
EABCAB
EABCBA
EABCBB
EABDAA
EABDBA
EBBAAA
EBBAAB
EBBABA
EBBABB
EBBCAA
EBBCAB
EBBCBA
EBBCBB
EBBDAA
EBBDBA
```

[End]

B.1.6.4 Listing of File 'SPTBR.RIS'

```
TB        LALH FOR SPECIAL PLANT CET BASE RISK              [Start]
          1                 46
AAAAAA   4.141E-02
AAABAA   8.525E-03
AAACAA   1.045E-01
AABAAA   0.000E+00
AABABA   8.428E-05
AABBAA   1.628E-04
AABBBA   3.332E-03
AABCBA   1.604E-02
BAAAAA   2.034E-01
BAABAA   1.386E-04
BAACAA   1.612E-01
BABAAA   3.251E-03
BABABA   5.450E-02
BABBAA   1.808E-05
BABBBA   2.379E-04
BABCAA   3.247E-04
BABCBA   2.424E-02
DAAAAA   5.402E-03
DAABAA   2.801E-05
DAACAA   5.042E-03
DABAAA   8.865E-03
DABABA   1.249E-01
DABBAA   5.059E-04
DABBBA   5.375E-03
DABCAA   1.024E-03
DABCBA   5.287E-02
DBBAAA   1.475E-03
DBBABA   4.652E-03
DBBBAA   1.753E-05
DBBBBA   1.595E-04
DBBCAA   4.511E-04
DBBCBA   1.462E-03
EAAAAA   2.244E-03
EAACAA   2.564E-02
EABAAA   3.481E-04
EABABA   9.278E-03
EABCAA   4.061E-04
EABCBA   1.175E-02
EABDAA   3.481E-03
EABDBA   3.174E-02
EBBAAA   5.603E-03
EBBABA   5.124E-02
EBBCAA   1.750E-03
EBBCBA   1.617E-02
EBBDAA   2.919E-04
EBBDBA   2.775E-03
```

```
             2              46
AAAAAA  2.175E-02
AAABAA  1.638E-03
AAACAA  1.723E-02
AABAAA  0.000E+00
AABABA  3.659E-03
AABBAA  3.069E-05
AABBBA  6.751E-04
AABCBA  3.757E-03
BAAAAA  4.009E-01
BAABAA  5.447E-04
BAACAA  9.781E-02
BABAAA  6.138E-03
BABABA  1.075E-01
BABBAA  1.028E-04
BABBBA  1.035E-03
BABCAA  6.503E-04
BABCBA  1.946E-02
DAAAAA  6.485E-03
DAABAA  9.770E-05
DAACAA  2.103E-03
DABAAA  7.078E-03
DABABA  1.260E-01
DABBAA  1.098E-03
DABBBA  1.133E-02
DABCAA  4.584E-04
DABCBA  2.464E-02
DBBAAA  2.411E-05
DBBABA  4.393E-04
DBBBAA  0.000E+00
DBBBBA  0.000E+00 ·
DBBCAA  0.000E+00
DBBCBA  1.208E-04
EAAAAA  2.284E-03
EAACAA  6.997E-03
EABAAA  1.551E-03
EABABA  2.832E-02
EABCAA  4.693E-04
EABCBA  1.047E-02
EABDAA  6.638E-04
EABDBA  6.086E-03
EBBAAA  5.527E-03
EBBABA  5.038E-02
EBBCAA  1.744E-03
EBBCBA  1.590E-02
EBBDAA  3.573E-04
EBBDBA  3.343E-03
```
[File continues similarly for each sample member]

[Containment failure probability files for other plant damage states are similar]

B.1.6.5 Listing of File 'SPFINAL.CLS'

```
SPECIAL PLANT FINAL CLUSTERS #  1                    [Start]
        24       13950 0.00000E+00
     12       15       16       10       10       12       18       18       16       18       16
     16       10       15       14        8        8       12       18       18       18       16
  18       10       16       16       12       15       15       10       10       13       17
  17       18       17       12       15       15       12       15       15       17       10       10
     13       17       17       17       16       17       17       17       12       12       15
  15       17       18       18       18       18       18       18       18       17       17
  17       17       17       17       15       15       17       17       17       17       15       15
     17       17       24       24                 [End of cluster file for first
                                                    sample  member.  Continues.
                                                    similarly  for  all  sample
                                                    members]
```

B.1.6.6 Listing of File 'MACCS_SPEC.OUT'

```
SPEC  1G                                              [Start]
2.37E+02
1.11E+03
2.00E-03
1.92E+04
3.60E+07
3.55E+10
SPEC 2G
2.25E+02
1.02E+03
2.38E-03
1.68E+04
3.47E+07
3.35E+10
SPEC 3G
8.32E+01
5.32E+02
1.96E-03
1.66E+04
3.16E+07
2.15E+10
SPEC 4G
3.17E+01
2.78E+02
1.72E-03
1.48E+04
2.82E+07
1.36E+10
SPEC 5G
2.06E+01
1.94E+02
1.57E-03
1.21E+04
2.70E+07
1.09E+10
SPEC 6G
5.47E+00
6.31E+01
1.12E-03
1.09E+04
2.38E+07
7.15E+09
SPEC 7G
2.98E-01
6.08E+00
7.17E-04
1.33E+04
1.76E+07
```

```
6.80E+09
SPEC 8G
2.84E-01
6.32E+00
6.37E-04
1.01E+04
1.68E+07
4.09E+09
SPEC 9G
2.14E-01
1.93E+00
5.72E-04
7.48E+03
1.34E+07
2.48E+09
SPEC 10G
7.91E-02
3.90E-01
2.45E-04
9.92E+03
9.28E+06
5.62E+09
SPEC 11G
2.36E-01
2.68E+00
5.53E-04
2.20E+03
3.13E+06
4.73E+08
SPEC 12G
7.61E-02
3.80E-01
2.27E-04
7.81E+03
8.19E+06
3.67E+09
SPEC 13G
4.40E-02
3.02E-01
2.41E-04
6.17E+03
8.59E+06
1.56E+09
SPEC 14G
2.38E-02
1.58E-01
1.46E-04
5.09E+03
6.07E+06
1.93E+09
SPEC 15G
2.04E-02
```

2.13E-01
1.12E-04
2.25E+03
3.49E+06
4.42E+08
SPEC 16G
8.03E-03
7.83E-02
5.84E-05
4.25E+03
5.23E+06
1.35E+09
SPEC 17G
4.95E-02
3.23E-01
1.66E-04
6.61E+02
1.21E+06
1.80E+08
SPEC 18G
6.11E-03
1.03E-01
5.67E-05
2.04E+03
2.88E+06
3.94E+08
SPEC 19G
4.82E-04
1.56E-02
6.13E-06
3.07E+03
3.68E+06
5.69E+08
SPEC 20G
8.44E-03
1.33E-01
5.38E-05
6.95E+02
1.06E+06
1.57E+08
SPEC 21G
3.57E-03
8.09E-02
3.06E-05
4.04E+02
6.71E+05
1.15E+08
SPEC 22G
1.29E-04
8.02E-03
1.98E-06
2.05E+03

```
2.55E+06
3.96E+08
SPEC 23G
5.96E-06
1.76E-03
9.17E-08
5.01E+02
8.34E+05
1.00E+08
SPEC 24G
0.00E+00
0.00E+00
0.00E+00
3.16E-01
6.89E+02
6.74E+05                                        [End]
```

B.1.7 Parameter Values (Dimensions)

The user will find that parameter values will have to be adjusted for each
specific plant. Parameters--maximum permissible dimensions--are found in two
locations, and it is imperative that they be consistent. All parameters are
found at the head of the main routine. Parameters are not passed to subroutines
via commons or formal parameters, but by an 'include' statement at the beginning
of each subroutine. The 'included' parameters are found in GENPARAM2.FOR, which
must be identical with the parameter set in the main routine. It is suggested
the first parameter set (in the main routine) be duplicated and copied into the
file GENPARAM2.FOR. Note that any changes must be made identically in both
locations.

The user should note that many arrays are triply dimensioned. Overly exuberant
setting of parameters could quickly exceed the storage limitations of any system,
however large. Maximum dimensions should be set only as large as is required for
each specific plant.

B.1.8 References

1. Breeding, R. J., et al., _Evaluation of Severe Accident Risks: Surry Unit 1_, NUREG/CR-4551, SAND86-1309, Vol. 3, Revision 1, Sandia National Laboratories, Albuquerque, NM, October 1990.

2. Payne, Jr., A. C., et al., _Evaluation of Severe Accident Risks: Peach Bottom Unit 2_, NUREG/CR-4551, SAND86-1309, Vol. 4, Revision 1, Sandia National Laboratories, Albuquerque, NM, December 1990.

3. Gregory, J. J., et al., _Evaluation of Severe Accident Risks: Sequoyah Unit 1_, NUREG/CR-4551, SAND86-1309, Vol. 5, Revision 1, Sandia National Laboratories, Albuquerque, NM, December 1990.

4. Brown, T. D., et al., _Evaluation of Severe Accident Risks: Grand Gulf Unit 1_, NUREG/CR-4551, SAND86-1309, Vol. 6, Revision 1, Sandia National Laboratories, Albuquerque, NM, December 1990.

5. Park, C. K., et al., _Evaluation of Severe Accident Risks: Zion Unit 1_, NUREG/CR-4551, BNL-NUREG-52029, Vol. 7, Revision 1, Brookhaven National Laboratories, March 1993.

6. Iman, R. L., J. D. Johnson and J. C. Helton, _A User's Guide for the Probabilistic Risk Assessment Model Integration System (PRAMIS)_, NUREG/CR-5262, SAND88-3093, Sandia National Laboratories, Albuquerque, NM, 1990.

7. Iman, R. L. and M. J. Shortencarier, _A FORTRAN 77 Program and User's Guide for the Generation of Latin Hypercube and Random Samples for Use with Computer Models_, NUREG/CR-3624, SAND83-2365, Sandia National Laboratories, Albuquerque, NM, 1984.

B.2 Listing of the RISQUE Code

```
        PROGRAM RISKEE
C****************************************************************
C       Risk Integration System for Quantitative Uncertainty Evaluation
C       A code for Latin Hypercube evaluation of the risk due to
C       nuclear power plants, written by Walter B. Murfin, a
C       consultant to Organization 6411, Sandia National Laboratories,
C       Albuquerque, NM, February, 1986.
C       THIS PROGRAM CALCULATES RISK FOR EACH MEMBER OF A SAMPLE,
C       WHERE A SAMPLE MEMBER CONSISTS OF A SET OF CHOICES FROM
C       EACH OF A SET OF VECTORS OF SEQUENCE FREQUENCY, CONTAIN-
C       MENT FAILURE MODES, RELEASES, AND CONSEQUENCES.  THE PRO-
C       GRAM CALCULATES RISK FOR EACH SAMPLE MEMBER, DETERMINES
C       THE CUMULATIVE PROBABILITY DISTRIBUTION, AND FINDS THE
C       5TH-/50TH-/95TH-PERCENTILES, MEAN, AND VARIANCE OF THE
C       SAMPLE.
c****************************************************************
C       THE FOLLOWING PARAMETERS MUST ALSO APPEAR IN "GENPARAM2.FOR"
C****************************************************************
C****************************************************************
C
        PARAMETER(
C          MAXIMUM SAMPLE SIZE
     $    MAXSAMP=200,
C          MAXIMUM NUMBER OF FREQUENCY PHEN. VECTORS
     $    MAXSEQVECT=65,
C          MAXIMUM NUMBER OF CFM VECTORS
     $    MAXCFMVECT=200,
C          MAXIMUM NUMBER OF RELEASE VECTORS
     $    MAXRELVECT=65,
C          MAXIMUM NUMBER OF CONSEQUENCE VECTORS
     $    MAXCSQVECT=1,
C        MAXIMUM NUMBER OF ISSUE GROUPS
     $        MAXISSGP=5,
C        MAXIMUM NUMBER OF ISSUES FOR EACH ISSUE GROUP
     $        MAXISS=20,
C        MAXIMUM NUMBER OF LEVELS FOR EACH ISSUE
     $        MAXLVL=10,
c        maximum number of alternatives for each base case
     $        maxalt=1,
c        maximum number of containment failure mode groups
     $        maxcfg=7,
c        maximum number of containment failure modes
     $        maxcfm=2000,
c          AVERAGE NUMBER OF BINS PER CFG
     $    MAVPCFG=200,
c        maximum number of consequences
     $        maxcsq=9,
c        maximum number of release fraction groups
     $        maxrel=65,
c        maximum number of sequences
```

B.28

```
      $           maxseq=7,
c         maximum number of input cost points
      $   maxcostin=3)
C*********************************************************************
C     END OF PARAMETER SET
C*********************************************************************
C                           .
C
C*********************************************************************
C     THE FOLLOWING STATEMENTS MUST ALSO APPEAR IN "EXPLAN2.FOR"
C*********************************************************************
C*********************************************************************
C
C
C
c these are several literals, or parameters in fortranese, so that the
c program may be readily modified for larger (or smaller) storage
c requirements
c*********************************************************************


c*********************************************************************
c Basic information
      character*80
c         NAMe of ALTernative to base case
      $  namalt,
c         NAMe of BASe case
      $  nambas

      integer
c      number of alternatives to current base case
      $      numalt,
c      number of base cases in data base
      $      numbas,
c      number of containment failure groups
      $      numcfg,
c      number of containment failure modes
      $      numcfm,
c      number of consequence measures (must be same for base case its
c      alternatives)
      $      numcsq,
c       number of radioactive releases (CRAC runs) in data base
      $  numrel,
c      number of sequences for current case
      $      numseq,
C       SAMPLE SIZE FOR CURRENT CASE
      $  NUMSAMP
c*********************************************************************


c*********************************************************************
c Sequence Descriptor

      character*80
```

```
c      NAMe of SEQuence
$          namseq(maxseq)
 real
C
C        SEQUENCE FREQUENCIES FOR CURRENT CASE (FS) & BASE (FBS)
C        AND MELTDOWN FREQUENCIES (FMD & FBMD)
   $   FS(MAXSAMP,MAXSEQ),FBS(MAXSAMP,MAXSEQ),
   $   FMD(MAXSAMP),FBMD(MAXSAMP),
C        MULTIPLIERS (HI & LOW) FOR CORE MELT FREQUENCIES TO
C        REFLECT DATA UNCERTAINTY
   $   SEQMULLO,SEQMULHI
C
  integer
C        INDEX OF POINTER FROM CONTAINMENT FAILURE MODE (CFM)
C        TO RELEASES FOR CURRENT CASE (IRSM) AND BASE
C        CASE (IRBSM)
   $   IRSM(MAXSAMP,MAXCFM),
   $   IRBSM(MAXSAMP,MAXCFM),
c      Index of Containment Failure Group for Sequence
   $          icfgs(maxseq), icfgbs(maxseq)
C
c End of sequence descriptor
c*************************************************************************

c*************************************************************************
c Containment Failure Group

  character*20
c      NAMe of Containment Failure Group
   $          namcfg(maxcfg)
C    real
C    PROBABILITY OF CONTAINMENT FAILURE FOR EACH CFM VECTOR AND
C    CONTAINMENT FAILURE MODE, FOR THE CURRENT CASE (PFGM)
C    AND BASE CASE (PFBGM)
C    $   PFGM(MAXSAMP,MAXCFG,MAXCFM), ==> FUNCTION
C    $   PFBGM(MAXSAMP,MAXCFG,MAXCFM) ==> FUNCTION
C
c*************************************************************************
c Consequence Data

  character*80
c      Names of consequence measures
   $   namcsq(maxcsq)
C
c*************************************************************************
c CRAC data

  character*20
c      NAMe of radioactive Release (CRAC run)
   $          namrel(maxrel)
C
  real
```

```
c          MEAN CONSEQUENCE FOR CONSEQUENCE VECTOR ICSQVECT, CON
c          SEQUENCE MEASURE ICSQ, RELEASE IREL =
c          CR(ICSQVECT,IREL,ICSQ)=CR(IREL,ICSQ)
c          THE CONSEQUENCE CALCULATIONS ARE NOT SAMPLED
      $   CR(MAXREL,MAXCSQ),CRB(MAXREL,MAXCSQ)
c end of CRAC data.
c*******************************************************************

c*******************************************************************
c Risk group

      real
c       RISK FOR SAMPLE MEMBER ISAMP, CONSEQUENCE MEASURE ICSQ
c       = R (ISAMP,ICSQ)
      $  R(MAXSAMP,MAXCSQ),RB(MAXSAMP,MAXCSQ),
c       CONTRIBUTION TO RISK FOR SEQUENCE ISEQ
c       = RSEQ(ICSQ,ISEQ)
      $  RSEQ(MAXCSQ,MAXSEQ),
c     CONTRIBUTION TO RISK FOR CFM ICFM
c     =RCFM(ICSQ,ICFM)
      $      RCFM(MAXCSQ,MAXCFM),
c     CONTRIBUTION TO RISK FOR RELEASE CATEGORY JREL
c     = RREL(ICSQ,JREL)
      $      RREL(MAXCSQ,MAXREL),
c       PROBABILITY ASSOCIATED WITH MEMBER ISAMP
      $  PROB(MAXSAMP),
c       CHANGE IN RISK FOR SAMPLE MEMBER ISAMP, CONSEQUENCE ICSQ
c     DUE TO SAFETY OPTION = DR(ISAMP;ICSQ)
      $      DR(MAXSAMP,MAXCSQ),
c     LEVELS, FOR RATIO OR INTERVAL VARIABLES (PHYSICAL QUANTITIES)
      $      SLVL(MAXISS,MAXISSGP,MAXLVL)
c end of risk group
c*******************************************************************
c working variables

c          ****************************************
      integer
c     POINTERS
c     poiNter to Containment Failure Group for current sequence
      $      ncfg,
c          ****************************************
c     LOOP COUNTERS
c     index for safety alternatives in current base case
      $      ialt,
c     index for base cases
      $  ibas,
c     index over containment failure mode groups
      $      icfg,
c     index over conmtainment failure modes
      $  icfm,
c     Index over consequence measures
      $      icsq,
```

```
c        Index over radioactive releases (CRAC runs)
      $  irel,
c      index over sequences
      $       iseq,
C        INDEX OVER SAMPLE MEMBERS
      $  ISAMP
c            ***********************************************
         CHARACTER*80 NAMISSGP,NAMISS
C        ***********************************************
c      FLAGS

         logical
c      flag for base case, true=base case, false=safety alternative
      $       base,
C      FLAG FOR NOMINAL VARIABLES (TRUE=NOMINAL OR ORDINAL VAR.,
C      FALSE=INTERVAL OR RATIO VAR.)
      $       NOMINAL(MAXISS,MAXISSGP)
C***********************************************************************
C      END OF "EXPLAN2" SET
C***********************************************************************
C
C
c***********************************************************************
C      THE FOLLOWING COMMON STATEMENTS MUST ALSO APPEAR IN
C      "GENCOM2.FOR"
c***********************************************************************
c***********************************************************************
c COMMONS

c all variables except working variables are included in the commons
c any working variable needed by a subroutine should be passed
c explicitly.

         common
      $  /SAMPCOM/ISEQSAMP(MAXSAMP),ICFMSAMP(MAXSAMP),
      $            IRELSAMP(MAXSAMP),ICSQSAMP(MAXSAMP),
      $            NUMISSGP,NUMISS(MAXISSGP),
      $            LVL(MAXISSGP,MAXISS,MAXSAMP),
      $            NUMLVL(MAXISS,MAXISSGP),
      $            NUMCSQVECT,NUMSEQVECT,NUMRELVECT,
      $            NUMCFVECT,SLVL,NOMINAL,
      $            ISEQNUM,ICFNUM,IRNUM,ICSQNUM
      $  /CRACom/CR,CRB
      $  /fcom/  FS,FBS,FMD,FBMD,SEQMULLO,SEQMULHI
      $  /ifcom/ icfgbs,icfgs
      $  /ircom/ IRSM,IRBSM
      $  /namcom/namalt,nambas,namcfg,namrel,namseq,namcsq,
      $            NAMISSGP(MAXISSGP),NAMISS(MAXISS,MAXISSGP)
      $  /numcom/numalt,numbas,numcfg,numcfm,numcsq,numdpt,numfcg,numrel,
      $            numseq,NUMSAMP
      $  /pfcom/ ISLAST,LASTPBN,PROBIN(MAXCFM,MAXCFG),
      $            IPOINT(MAXCFG*MAXSAMP*MAVPCFG*2),NBINS(MAXCFG,MAXSAMP),
```

```
      $            PRBLST(MAXCFG*MAXSAMP*MAVPCFG*2),
      $            ISTRTG(MAXCFG,MAXSAMP),ISTRTGB(MAXCFG,MAXSAMP),
      $            NEXTFRE
      $  /Rcom/  R,RB,RCON,PROB,RSEQ,RREL,RCFM,   DR
      $  /VCOM/
      $         KDOS,AVONSDOS,DOSINST,DOSOPER,
      $         KFAT,KILL,KLAT
      $  /costcom/jblt,juslif,jpres,pmwe,capf,discr,escr,
      $  PPCI(MAXCOSTIN),CPKWI(MAXCOSTIN),CCUP(MAXCOSTIN),
      $  CDEC(MAXCOSTIN),OSHC(MAXCOSTIN),KCOS,
      $  AVCRP,AVCAP
      $   ,CINST(MAXCOSTIN),COPER(MAXCOSTIN),
      $      TRPINST(MAXCOSTIN),TRPOPER(MAXCOSTIN),
      $  /OPTCPM/IOPT(13),IUSE(MAXSEQ),NUMSEL,ISEL(MAXSAMP)
        LOGICAL IOPT,IUSE
C****************************************************************
C     END OF COMMON STATEMENTS
C****************************************************************
C
c
c     open necessary input and output files
      open(unit=1,file='output',status='NEW')
      open(unit=2,file='infile.dat',status='old')
      OPEN(UNIT=3,FILE='PLOTOUT',STATUS='NEW')
C
      READ(2,*)NUMBAS
c     Loop over all the cases
      DO 30 ibas=1,numbas
c      set base case flag to base case for first time through next
c      loop
       base=.true.
C      READ BASE CASE DATA
         NEXTFRE=1
       CALL REDATA(BASE)
         NEXTFRES=NEXTFRE
       WRITE(3,5450)
5450   FORMAT(1H1,4X,'BASIC PRELIMINARY DATA'//)
       WRITE(3,5455)NUMSAMP
5455   FORMAT(5X,'THE SAMPLE SIZE IS ',I3/)
       WRITE(3,5460)NUMISSGP,(NAMISSGP(ISSGP),ISSGP=1,NUMISSGP)
5460   FORMAT(5X,'THE FOLLOWING ',I2,' GROUPS OF ISSUES'
      $    ' HAVE BEEN VARIED :'/(5X,A80/))
       DO 546 ISSGP=1,NUMISSGP
         WRITE(3,5465)ISSGP,NUMISS(ISSGP)
5465     FORMAT(//5X,'ISSUE GROUP NO. ',I2,' HAS ',I2,
      $             ' ISSUES')
         DO 547 ISS=1,NUMISS(ISSGP)
           WRITE(3,5470)ISS,NUMLVL(ISS,ISSGP),NAMISS(ISS,ISSGP)
5470       FORMAT(10X,'ISSUE NO. ',I2,' HAS ',I2,' LEVELS'/
      $             10X,'THE ISSUE IS: ',A80)
547      CONTINUE
546    CONTINUE
```

```
c          Loop over all safety alternatives
      DO 20 ialt=0,numalt
C     READ DATA FOR SAFETY OPTION
            NEXTFRE=NEXTFRES
            IF(.NOT.BASE)CALL REDATA (BASE)
C     CALCULATE RISK
                 call point
C     OUTPUT CORE MELT FREQUENCIES AND RISKS
              CALL OUTRISK(BASE)
            CALL OUTCOST(BASE,DISCAV)
C     IF SAFETY OPTION, CALCULATE RISK REDUCTION
            IF(.NOT.BASE)CALL RISKRED
C     IF SAFETY OPTION, CALCULATE COST:BENEFIT MEASURES
            IF(.NOT.BASE) CALL COSTBEN(DISCAV)
c          reset base so that following passes through this loop
c          indicate a safety alternative
            IF(BASE) THEN
              BASE=.FALSE.
C     SET BASE CASE DATA
              DO 100 ISEQ=1,NUMSEQ
                ICFGBS(ISEQ)=ICFGS(ISEQ)
                DO 110 ISAMP=1,NUMSAMP
                     FBS(ISAMP,ISEQ)=FS(ISAMP,ISEQ)
110               CONTINUE
100             CONTINUE
              DO 1765 ISAMP=1,NUMSAMP
                DO·120 ICFM=1,NUMCFM
                   IRBSM(ISAMP,ICFM)=
     $                       IRSM(ISAMP,ICFM)
120               CONTINUE
                DO 130 ICFG=1,NUMCFG
                     ISTRTGB(ICFG,ISAMP)=ISTRTG(ICFG,ISAMP)
130               CONTINUE
                FBMD(ISAMP)=FMD(ISAMP)
                DO 170 ICSQ=1,NUMCSQ
                   RB(ISAMP,ICSQ)=R(ISAMP,ICSQ)
170               CONTINUE
1765          CONTINUE
              DO 187 IREL=1,NUMREL
                DO 180 ICSQ=1,NUMCSQ
                   CRB(IREL,ICSQ)=
     $                       CR(IREL,ICSQ)
180               CONTINUE
187             CONTINUE
            ENDIF
C
                ISLAST=0
c          end of loop over safety alternatives
   20        CONTINUE
c        end of loop over base cases, get next case if there are more.
30      CONTINUE
        END
```

```
      subroutine redata(base)
C     READ INPUT DATA FOR BASE CASE AND SAFETY OPTIONS, FOR
C     LIMITED LATIN HYPERCUBE SAMPLING.  EACH SAMPLE MEMBER
C     CONSISTS OF A DIRECTED CHOICE FROM EACH OF A SET OF
C     VECTORS OF FREQUENCY, CFM, RELEASE, AND CONSEQUENCE
C     DATA.
C
C*******************************************************************
C     CAUTION!! HAS EVERYTHING IN THE PARAMETER, EXPLANATORY, AND
C     COMMON STATEMENTS OF THE MAIN PROGRAM BEEN PUT INTO
C     "GENPARAM2.FOR", "EXPLAN2.FOR", AND "GENCOM2.FOR"?
C*******************************************************************
C
      INCLUDE 'GENPARAM2.FOR'
      INCLUDE 'EXPLAN2.FOR'
      INCLUDE 'GENCOM2.FOR'
      DIMENSION CFMN(MAXCFG,MAXCFM)
      CHARACTER*80 HDR_WORDS,SEQ_WORDS,CFM_WORDS,CONS_WORDS,REL_WORDS,
     $ GARBAGE
      CHARACTER*50 TEMFIL,CODEFIL,CFGFIL(MAXCFG),POINTFIL,
     $           CODE(MAXCFM),PBINFIL,VECTFIL,CONSFIL
      COMMON/CODECOM/CODE,LCODE
C
C     VECTFIL=NAME OF FILE ON WHICH SAMPLE VECTORS ARE FOUND
C     TEMFIL=NAME OF FILE ON WHICH TEMAC DATA IS FOUND
C     CODEFIL=NAME OF FILE ON WHICH BIN CODES ARE FOUND
C     CFGFIL(ARRAY)=NAMES OF FILES ON WHICH EVENTRE OUTPUTS ARE FOUND
C             (ONE FOR EACH PLANT DAMAGE STATE)
C     POINTFIL=NAME OF FILE ON WHICH BIN-CLUSTER POINTERS ARE FOUND
C     CONSFIL=NAME OF FILE ON WHICH CONSEQUENCES ARE FOUND
C
C
C     SET FLAGS
      LOGICAL ICHGSEQ,ICHGCFM,ICHGREL,TEST,
     $         SIGSEQ(MAXSAMP),SIGCFM(MAXSAMP,MAXCFG),SIGREL(MAXSAMP),
     $     SIGCSQ(MAXSAMP)
      DIMENSION IRIN(MAXCFM),ILVL(MAXLVL)
C     FOR SAFETY OPTIONS, ICFGCHG IS THE LIST OF CONTAINMENT FAILURE
C     GROUPS (PLANT DAMAGE STATES) FOR WHICH CFM'S ARE TO BE CHANGED.
C     IRLPCHG IS THE LIST OF RELEASE POINTERS VECTORS FOR WHICH
C     RELEASE POINTERS ARE TO BE CHANGED.
      DIMENSION ICFGCHG(MAXCFG),IRLPCHG(MAXSAMP)
C
C
      logical err
      err=.false.

c     if this is a base case, get the base level information common
c     to all alternatives.

      if (base) then
c      get name of base case
```

B.35

```
       read(2,5000) nambas
          READ(2,5000)HDR_WORDS
C     GET NUMBER OF ALTERNATIVES, SAMPLE SIZE, CONTAINMENT FAILURE
C     GROUPS, CONTAINMENT FAILURE MODES, RELEASES, CONSEQUENCES,
      READ(2,*)NUMALT,NUMSAMP,NUMCFG,NUMCFM,NUMREL,NUMCSQ
      READ(2,*)KCOS,KDOS,KFAT,KILL,KLAT
5000  FORMAT(A80)
C     OUTPUT OPTIONS
C     IOPT(1)=.TRUE.; RISK CONDITIONAL ON CORE MELT, OTHERWISE ABSOLUTE
C          RISK PER YEAR
C     IOPT(2)=.TRUE.; A LIMITED SET OF SEQUENCES WILL BE USED, OTHERWISE
C          ALL SEQUENCES WILL BE USED
C     IOPT(3)=.TRUE.;BASE CASE RISK WILL BE PRINTED
C     IOPT(4)=.TRUE.; S.O. RISK WILL BE PRINTED
C     IOPT(5)=.TRUE.; S.O. DELTA-RISK (R0-R) WILL BE PRINTED
C     IOPT(6)=.TRUE.; S.O. RISK RATIO (R/R0) WILL BE PRINTED
C     IOPT(7)=.TRUE.; RISK WILL BE OUTPUT IN A FORM USEABLE BY "STEP"
C          STEPWISE MULTIPLE REGRESSION CODE
C     IOPT(8)=.TRUE.;CHI-SQUARED TEST OF SAMPLES MEMBERS BELOW/ABOVE
C          MEDIAN
C     IOPT(9)=.TRUE.; DETAILED ANALYSIS OF A SELECTED SET OF SAMPLE
C          MEMBERS
C     IOPT(10)=.TRUE.; A CCDF WILL BE CALCULATED FOR EACH SAMPLE
C     IOPT(11)=.TRUE.; PROBABILITY SUMS WILL BE NORMALIZED TO ONE
C     IOPT(12)=.TRUE.; PROBABILITY SUMS OUT OF TOLERANCE WILL ABORT
C       IOPT(13)=.TRUE.; BIN NOT IN BIN LIST WILL ABORT
C     MEMBER.  CCDFS ARE WRITTEN ON FILE CCDF.PLT.  INPUT FOR
C     CCDFS ON FILE CCDF.DAT.
      READ(2,5001)(IOPT(J),J=1,13)
5001  FORMAT(20L1)
         IF(IOPT(9))THEN
C     NUMSEL=NUMBER OF SAMPLE MEMBERS FOR DETAILED ANALYSIS (MAX=20)
         READ(2,*)NUMSEL
C     ISEL(JSEL); THE RISKS WILL BE SORTED IN ASCENDING ORDER, AND THE
C     ISEL-TH ***SORTED*** SAMPLE MEMBER WILL BE ANALYZED.  IF THE
C     LOWEST 10 SAMPLE MEMBERS (FOR EACH CONSEQUENCE MEASURE) ARE TO
C     BE ANALYZED, THEN ISEL=1 TO 10, ETC.
         READ(2,*)(ISEL(JSEL),JSEL=1,NUMSEL)
         ENDIF
      NUMSEQVECT=NUMSAMP
      NUMCFMVECT=NUMSAMP
      NUMRELVECT=NUMSAMP
C     READ IN INFORMATION ON ISSUES.
C          NUMBER OF ISSUE GROUPS
      READ(2,*)NUMISSGP
      READ(2,5000)(NAMISSGP(ISSGP),ISSGP=1,NUMISSGP)
      DO300 ISSGP=1,NUMISSGP
C     NUMBER OF ISSUES IN THIS GROUP, NUMBER OF LEVELS IN
C     EACH ISSUE
         READ(2,*)NUMISS(ISSGP),(NUMLVL(ISS,ISSGP),
     $               ISS=1,NUMISS(ISSGP))
C     READ IN NAMES OF ISSUES
```

```fortran
             DO 1555 ISS=1,NUMISS(ISSGP)
                READ(2,5000)NAMISS(ISS,ISSGP)
1555        CONTINUE
C     READ ISSUE LEVELS (PHYSICAL QUANTITIES) FOR RATIO OR
C     INTERVAL VARIABLES.  SKIP FOR NOMINAL OR ORDINAL
C     VARIABLES.
      READ(2,4563)(NOMINAL(ISS,ISSGP),ISS=1,NUMISS(ISSGP))
4563  FORMAT(10L1)
          DO 305 ISS=1,NUMISS(ISSGP)
             IF(.NOT.NOMINAL(ISS,ISSGP))
     $            READ(2,*)(SLVL(ISS,ISSGP,LEVEL),LEVEL=1,
     $               NUMLVL(ISS,ISSGP))
305         CONTINUE
300   CONTINUE
C     READ SAMPLE
C     EACH SAMPLE MEMBER INCLUDES ONE CHOICE FROM EACH OF THE
C     INPUT VECTOR SETS (SEQUENCES, CFM'S, RELEASES, CONSEQUENCES)
C     INPUT VECTOR IS ON FILE VECTFIL.  THE FILE NAME FOR
C     VECTFIL IS READ FROM UNIT 2 IN THE INPUT STREAM.
      READ(2,*)VECTFIL
      OPEN(UNIT=5,FILE=VECTFIL,STATUS='OLD')
      DO 60 ISAMP=1,NUMSAMP
C     READ IN SAMPLE MEMBER
      PROB(ISAMP)=1./NUMSAMP
C     READ IN ISSUE LEVELS FOR THIS SAMPLE MEMBER
      READ(5,*)((LVL(I,J,ISAMP),J=1,NUMISS(I)),I=1,NUMISSGP)
60    CONTINUE
      CLOSE(UNIT=5)
C     WRITE OUT SAMPLE CHOICES
C     WRITE OUT ISSUES AND LEVELS FOR ENTIRE SAMPLE.
      WRITE(1,3300)
3300  FORMAT(1H1,4X,'ISSUE LEVELS FOR ALL SAMPLE MEMBERS'/
     $       5X,'ISSGP',2X,'ISS',20X,'LEVELS')
      DO 80 ISSGP=1,NUMISSGP
          DO 82 ISS=1,NUMISS(ISSGP)
            IF(ISS.EQ.1)THEN
              WRITE(1,3309)ISSGP,ISS,NAMISS(ISS,ISSGP)
3309          FORMAT(/5X,2I5,5X,A80)
              WRITE(1,3310)ISSGP,ISS,(LVL(ISSGP,ISS,ISAMP),
     $                   ISAMP=1,NUMSAMP)
            ELSE
              WRITE(1,3319)ISS,NAMISS(ISS,ISSGP)
3319          FORMAT(10X,I5,5X,A80)
              WRITE(1,3320)ISS,(LVL(ISSGP,ISS,ISAMP),
     $                   ISAMP=1,NUMSAMP)
            ENDIF
3310  FORMAT(5X,2I5,': ',50I2/17X,50I2/17X,50I2/17X,50I2)
3320  FORMAT(10X,I5,': ',50I2/17X,50I2/17X,50I2/17X,50I2)
82          CONTINUE
80    CONTINUE
C      SEQUENCE DATA
C     READ THE NUMBER OF SEQUENCES
```

```
      READ(2,*)NUMSEQ
      SEQMULLO=1.
      SEQMULHI=1.
C     MODE GROUPS.
C
      DO 10 ISEQ=1,NUMSEQ
      READ(2,*)NAMSEQ(ISEQ),ICFGS(ISEQ)
10    CONTINUE
      READ(2,*)TEMFIL
      CALL RETEMAC(TEMFIL,SEQ_WORDS)
C     IF A LIMITED NUMBER OF SEQUENCES WILL BE USED, READ IN "IUSE"
C     IUSE(ISEQ)=.TRUE.; SEQUENCE(ISEQ) WILL BE USED
      IF(IOPT(2))THEN
      READ(2,5001)(IUSE(ISEQ),ISEQ=1,NUMSEQ)
      DO 11 ISEQ=1,NUMSEQ
        IF(IUSE(ISEQ))GOTO 11
        DO 111 ISAMP=1,NUMSAMP
          FS(ISAMP,ISEQ)=0.
111       CONTINUE
11    CONTINUE
      ELSE
      DO 12 ISEQ=1,NUMSEQ
        IUSE(ISEQ)=.TRUE.
12    CONTINUE
      ENDIF
C     THIS ENDS THE SEQUENCE DATA
C
C     NOW READ THE CONTAINMENT FAILURE MODE DATA
      READ(2,*)CODEFIL
      CALL RECODES(CODEFIL,CODE,CFM_WORDS,LCODE)
      DO 9938 ICFG=1,NUMCFG
        READ(2,*)CFGFIL(ICFG)
        PBINFIL=CFGFIL(ICFG)
        CALL REDEVNT(PBINFIL,CODE,ICFG,LCODE)
9938  CONTINUE
      ISLAST=0
      NEXTFRE=LASTPBN+1
C     FIND MEAN CONTAINMENT FAILURE PROBABILITIES FOR EACH CFG
      DO 994 ICFG=1,NUMCFG
        DO 995 ICFM=1,NUMCFM
          CFMN(ICFG,ICFM)=0.
995     CONTINUE
994   CONTINUE
        DO 998 ISAMP=1,NUMSAMP
          DO 997 ICFG=1,NUMCFG
          DO 996 ICFM=1,NUMCFM
            CFMN(ICFG,ICFM)=CFMN(ICFG,ICFM)+PFGM(ISAMP,ICFG,ICFM)/
     $            NUMSAMP
996       CONTINUE
997       CONTINUE
998     CONTINUE
C
```

```
C       END OF CONTAINMENT FAILURE MODE DATA
C
C       READ IN POINTERS FROM CFM'S TO RELEASES.
        READ(2,*)POINTFIL
        CALL REDPOINT(POINTFIL,REL_WORDS)
C
C       END OF RELEASE POINTER DATA
C
C       READ CONSEQUENCE DATA
C       READ NUMBER OF CONSEQUENCE FILES (USUALLY 1)
        READ(2,*)NUMCSQVECT
        READ(2,5000)CONS_WORDS
C       FIRST, READ CONSEQUENCE DESCRIPTION
C       READ CONSEQUENCE NAMES
        DO 8822 ICSQ=1,NUMCSQ
        READ(2,5000)NAMCSQ(ICSQ)
8822    CONTINUE
        DO 8821 ICSQVECT=1,NUMCSQVECT
        READ(2,*)CONSFIL
        CALL REDCONS(CONSFIL,ICSQVECT)
8821    CONTINUE
C
C    END OF CONSEQUENCE DATA
C
C        Input cost data
C       FOR INPUT COST DATA, SEE BURKE (NUREG/CR-3673), AND
C       STRIP (NUREG/CR-2723).
C        JBLT: Year plant started on-line.
C        JUSLIF: Estimated number of years of useful life,
C        measured from JBLT.
C        JPRES: Present year
C        PMWE: Plant power (MWe)
C        CAPF: Average plant capacity factor, %
C        DISCR: discount rate
C        ESCR: fossil fuel cost escalation rate
C        PPCI: initial power cost differential (O,C,P)
C        CPKWI: Cost per kilowatt installed (plant cost) (O,C,P)
C        CCUP: Cost of cleanup (O,C,P)
C        CDEC: cost of decommissioning (O,C,P)
C        OSHC: on-site health costs (O,C,P)
        READ (2,*)JBLT,JUSLIF,JPRES
        READ(2,*)PMWE,CAPF,DISCR,ESCR
        READ(2,*)(PPCI(I),I=1,3)
        READ(2,*)(CPKWI(I),I=1,3)
        READ(2,*)(CCUP(I),I=1,3)
        READ(2,*)(CDEC(I),I=1,3)
        READ(2,*)(OSHC(I),I=1,3)
         if (err) stop
        WRITE(1,6000)NAMBAS,HDR_WORDS,SEQ_WORDS,CFM_WORDS,
     $ REL_WORDS,CONS_WORDS
6000  FORMAT('1    BASE CASE: ',A20/
     $ 5X,'Specific information concerning input data follows :'/
```

```
     $ 5X,'HEADER : ',A80/5X,'SEQUENCES : ',A80/
     $ 5X,'CONTAINMENT FAILURE MODES : ',A80/
     $ 5X,'RELEASES : ',A80/
     $ 5X,'CONSEQUENCES : ',A80)
C     WRITE OUT MEAN CFM FREQUENCIES FOR EACH CFG
      WRITE(1,6001)
6001  FORMAT('1    MEAN CFM PROBABILITIES FOR EACH CFG')
      DO 6002 ICFG=1,NUMCFG
        WRITE(1,6003)ICFG,(CFMN(ICFG,ICFM),ICFM=1,NUMCFM)
6003    FORMAT(/5X,'ICFG = ',I2/(5F7.4,5X,5F7.4))
6002  CONTINUE
C     WRITE OUTPUT OPTIONS
      IF(IOPT(1))THEN
        WRITE(1,6004)
6004    FORMAT(/5X,'RESULTS ARE RISK CONDITION ON CORE MELT')
      ELSE
        WRITE(1,6005)
6005    FORMAT(/5X,'RESULTS ARE ABSOLUTE RISK PER YEAR')
      ENDIF
      IF(IOPT(2))THEN
        WRITE(1,6006)
6006    FORMAT(/5X,'A LIMITED SUBSET OF SEQUENCES LISTED BELOW WILL'
     $          ,' BE USED')
        DO 500 ISEQ=1,NUMSEQ
          IF(IUSE(ISEQ))WRITE(1,550)NAMSEQ(ISEQ)
550       FORMAT(5X,A)
500     CONTINUE
      ENDIF
      IF(IOPT(3))WRITE(1,6007)
6007  FORMAT(/5X,'BASE CASE OUTPUT WILL BE PRINTED')
      IF(NUMALT.GT.0)THEN
        IF(IOPT(4))WRITE(1,6008)
6008    FORMAT(/5X,'SAFETY OPTION RISK WILL BE PRINTED')
        IF(IOPT(5))WRITE(1,6009)
6009    FORMAT(/5X,'SAFETY OPTION DELTA-RISK (R0-R) WILL BE PRINTED')
        IF(IOPT(6))WRITE(1,6010)
6010    FORMAT(/5X,'SAFETY OPTION RISK RATIO (R/R0) WILL BE PRINTED')
        IF(.NOT.(IOPT(4).OR.IOPT(5).OR.IOPT(6)))WRITE(1,6011)
6011    FORMAT(/5X,'ONLY S.O. COSTS & BENEFITS WILL BE WRITTEN')
      ENDIF
      IF(IOPT(7))WRITE(1,6012)
6012  FORMAT(/5X,'RISK WILL BE WRITTEN OUT IN A FORM USEABLE BY THE ',
     $          '"STEP" STEPWISE MULTIPLE REGRESSION CODE'/
     $          5X,'ON FILE STEPOUT.DAT.')
C
C     END OF BASE CASE
C
      ELSE
C     SAFETY OPTION; READ NEW DATA AS REQUIRED
      READ(2,5000)NAMALT
      READ(2,*)UNAVAIL
      AVAIL=1.-UNAVAIL
```

```
        READ(2,4000)ICHGSEQ,ICHGCFM,ICHGREL
4000    FORMAT(3L1)
C       FIRST,SET ALL DATA EQUAL TO BASE CASE
C       FREQUENCIES
        DO 400 ISAMP=1,NUMSAMP
          DO 410 ISEQ=1,NUMSEQ
            FS(ISAMP,ISEQ)=FBS(ISAMP,ISEQ)
410       CONTINUE
400     CONTINUE
C       CFM'S AND RELEASE POINTERS
        DO 420 ICFG=1,NUMCFG
          DO 430 ISAMP=1,NUMSAMP
            ISTRTG(ICFG,ISAMP)=ISTRTGB(ICFG,ISAMP)
430       CONTINUE
420     CONTINUE
        ISLAST=0
        DO 421 ISAMP=1,NUMSAMP
          DO 426 ICFM=1,NUMCFM
            IRSM(ISAMP,ICFM)=IRBSM(ISAMP,ICFM)
426       CONTINUE
421     CONTINUE
C       CONSEQUENCES
        DO 438 IREL=1,NUMREL
          DO 439 ICSQ=1,NUMCSQ
            CR(IREL,ICSQ)=CRB(IREL,ICSQ)
439       CONTINUE
438     CONTINUE
C
C       FREQUENCIES ARE TO BE CHANGED
        IF(.NOT.ICHGSEQ)GOTO 2366
C       RESET ALL FREQUENCIES
        READ(2,*)TEMFIL
        CALL RETEMAC(TEMFIL,SEQ_WORDS)
C
C       CFM'S ARE TO BE CHANGED
2366    IF(.NOT.ICHGCFM)GOTO 2367
C       RESET THOSE CFM'S TO BE CHANGED
        READ(2,*)NUMCFGCHG
C       NUMCFGCHG=NUMBER OF CONT. FAILURE GROUPS TO CHANGE
        ISSGP=2
        NUMBISS=NUMISS(ISSGP)
C       READ IN THE CFG'S WHICH WILL BE CHANGED
        READ(2,*)(ICFGCHG(ICF),ICF=1,NUMCFGCHG)
        DO 470 ICF=1,NUMCFGCHG
          ICFG=ICFGCHG(ICF)
          READ(2,*)PBINFIL
          CALL REDEVNT(PBINFIL,CODE,ICFG,LCODE)
C       END OF LOOP OVER CFM VECTORS
470     CONTINUE
        ISLAST=0
C       END OF LOOP OVER CONTAINMENT FAILURE GROUPS
C       THIS ENDS THE CFM DATA TO BE CHANGED.
```

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C
C     RELEASE POINTERS ARE TO BE CHANGED
2367  IF(.NOT.ICHGREL)GOTO 2368
C     RESET THOSE POINTERS TO BE CHANGED
          READ(2,*)NUMRELCHG
          READ(2,*)(IRLPCHG(I),I=1,NUMRELCHG)
          IRR=0
          DO 495 IRELCHG=1,NUMRELCHG
C     READ IN EACH VECTOR
              IREL=IRLPCHG(IRELCHG)
              READ(2,5050)GARBAGE,(ILVL(I),I=1,NUMBISS)
5050          FORMAT(A10,30(',',I1))
              READ(2,*)(IRIN(ICFM),ICFM=1,NUMCFM)
C     IS THIS VECTOR IN THE SAMPLE?
              DO 496 ISAMP=1,NUMSAMP
                 TEST=.TRUE.
                 DO 497 ISS=1,NUMBISS
                    IF(ILVL(ISS).NE.LVL(ISSGP,ISS,ISAMP))TEST=.FALSE.
497              CONTINUE
                 IF(TEST)THEN
C     STORE THIS VECTOR
                 DO 498 ICFM=1,NUMCFM
                    IRSM(ISAMP,ICFM)=IRIN(ICFM)
498              CONTINUE
                 ENDIF
496           CONTINUE
495        CONTINUE
2368  IF(.NOT.ICHGSEQ.AND..NOT.ICHGCFM.AND..NOT.ICHGREL)THEN
          TYPE*,'ERROR IN SAFETY OPTION INPUT'
          TYPE*,'NO CHANGES WERE SPECIFIED'
          STOP
      ENDIF
C      CINST = Cost of installation (O,C,P), $
C      COPER = Cost of operation (O,C,P), $/yr
C      TRPINST=Time out of service for inst., yr
C      TRPOPER=Time out of service for oper., yr/yr.
C      AVONSDOS=Averted onsite dose (plant life-time),p-rem
C      DOSINST=extra onsite dose in inst., p-rem
C      DOSOPER=extra onsite dose in oper., p-rem/yr
C
      READ(2,*)(CINST(J),J=1,MAXCOSTIN)
      READ(2,*)(COPER(J),J=1,MAXCOSTIN)
      READ(2,*)(TRPINST(J),J=1,MAXCOSTIN)
      READ(2,*)(TRPOPER(J),J=1,MAXCOSTIN)
      READ(2,*)AVONSDOS,DOSINST,DOSOPER
      ENDIF
      RETURN
      end

      SUBROUTINE POINT
C     THIS SUBROUTINE CALCULATES POINT VALUES OF RISK FOR A
C     MEMBER OF A SAMPLE.  EACH SAMPLE MEMBER IS GIVEN BY
```

```
C      A CHOICE OF A SINGLE VECTOR OF FREQUENCIES, CFM'S,
C      RELEASES, AND CONSEQUENCES.  POINT VALUES FOR EACH
C      SAMPLE MEMBER ARE CALCULATED FOR ALL CONSEQUENCE
C      MEASURES.
C      FMD(ISAMP)=MELTDOWN FREQUENCY FOR SAMPLE MEMBER ISAMP.
C      R(ISAMP,ICSQ)=RISK FOR SAMPLE MEMBER ISAMP, FOR CON-
C      SEQUENCE MEASURE ICSQ.
C****************************************************************
C      CAUTION!! HAS EVERYTHING IN THE PARAMETER, EXPLANATORY, AND
C      COMMON STATEMENTS OF THE MAIN PROGRAM BEEN PUT INTO
C      "GENPARAM2.FOR", "EXPLAN2.FOR", AND "GENCOM2.FOR"?
C****************************************************************
       INCLUDE 'GENPARAM2.FOR'
       INCLUDE 'EXPLAN2.FOR'
       INCLUDE 'GENCOM2.FOR'
C
C****************************************************************
C
C      ZERO OUT CONTRIBUTIONS FOR EACH SEQUENCE AND RELEASE.
       DO 4 ICSQ=1,NUMCSQ
            DO 6 ISEQ=1,NUMSEQ
                 RSEQ(ICSQ,ISEQ)=0.
6           CONTINUE
            DO 8 IREL=1,NUMREL
                 RREL(ICSQ,IREL)=0.
8           CONTINUE
            DO 88 ICFM=1,NUMCFM
                 RCFM(ICSQ,ICFM)=0.
88          CONTINUE
4      CONTINUE
C
C      LOOP OVER ALL SAMPLE MEMBERS
       DO 2 ISAMP=1,NUMSAMP
C      CALCULATE MELTDOWN FREQUENCY BY SUMMING OVER ALL SEQUENCES
       FMD(ISAMP)=0.0
         DO 10 ISEQ=1,NUMSEQ
         IF(.NOT.IUSE(ISEQ))GOTO 10
           FMD(ISAMP)=FMD(ISAMP)+FS(ISAMP,ISEQ)
10       CONTINUE
C
C      Calculate nominal risk, R(ISAMP,ICSQ)
       do 70 icsq=1,numcsq
        R(ISAMP,icsq)=0.0
C      STEP THROUGH SEQUENCES
         DO 60 iseq=1,numseq
          IF(.NOT.IUSE(ISEQ))GOTO 60
          DIVIDE=1.0
          IF(IOPT(1).AND.FMD(ISAMP).NE.0.0)DIVIDE=FMD(ISAMP)
C      SET CONTAINMENT FAILURE GROUP POINTER
          NCFG=ICFGS(ISEQ)
             do 50 icfm=1,numcfm
C      SET RELEASE POINTER
```

```
                  JRSM=IRSM(ISAMP,ICFM)
                  IF(JRSM.LE.0) GOTO 50
C     ADD THE CONTRIBUTION OF THIS TERM TO THE RISK.
                  TERCON=PFGM(ISAMP,NCFG,ICFM)*FS(ISAMP,ISEQ)
     $                *CR(JRSM,ICSQ)/DIVIDE
                  R(ISAMP,ICSQ)=R(ISAMP,ICSQ)+TERCON
C     ADD THE CONTRIBUTION OF THIS TERM TO THE PARTIAL CON-
C     TRIBUTION FOR THIS SEQUENCE
                  RSEQ(ICSQ,ISEQ)=RSEQ(ICSQ,ISEQ)+
     $                TERCON
C     ADD THE CONTRIBUTION OF THIS TERM TO THE PARTIAL CON-
C     TRIBUTION FOR THIS CFM.
                  RCFM(ICSQ,ICFM)=RCFM(ICSQ,ICFM)+
     $                 TERCON
C     ADD THE CONTRIBUTION OF THIS TERM TO THE PARTIAL
C     CONTRIBUTION FOR THIS RELEASE.
                  RREL(ICSQ,JRSM)=RREL(ICSQ,JRSM)+
     $                 TERCON
50                   CONTINUE
60                 CONTINUE
70        CONTINUE
2         CONTINUE
          RETURN
          END
          SUBROUTINE OUTRISK(BASE)
C     THIS SUBROUTINE CALCULATES RISK OUTPUT VALUES.
C****************************************************************
C     CAUTION!! HAS EVERYTHING IN THE PARAMETER, EXPLANATORY, AND
C     COMMON STATEMENTS OF THE MAIN PROGRAM BEEN PUT INTO
C     "GENPARAM2.FOR", "EXPLAN2.FOR", AND "GENCOM2.FOR"?
C****************************************************************
          INCLUDE 'GENPARAM2.FOR'
          INCLUDE 'EXPLAN2.FOR'
          INCLUDE 'GENCOM2.FOR'
          DIMENSION RS(MAXSAMP,MAXCSQ),PS(MAXSAMP,MAXCSQ),
     $ CUM(MAXSAMP),R05(MAXCSQ),R50(MAXCSQ),R95(MAXCSQ),
     $ RT(MAXSAMP),FMS(MAXSAMP),PFMS(MAXSAMP),
     $ CUMFMD(MAXSAMP) ,Y(MAXLVL+1,MAXSAMP),
     $ SENSMN(MAXLVL),XLVL(MAXLVL),ILVL(40),LVLORD(MAXLVL)
          DIMENSION PX(3*MAXSAMP),RX(3*MAXSAMP),PSENS(MAXSAMP),
     $     RSENS(MAXSAMP),XX(MAXSAMP),JSSNUM(MAXISS,MAXISSGP),
     $     XOUT(MAXISS*MAXISSGP+MAXCSQ)
          LOGICAL PP,PF,GOFRED
          CHARACTER*2 SIGWORD,INTERP,INTERPHI
          CHARACTER*20 KWORD
            CHARACTER*50 CODE,CODEX
          COMMON/CODECOM/CODE(MAXCFM),LCODE
          IF(BASE.AND.IOPT(7))THEN
          OPEN(UNIT=4,FILE='STEPOUT',STATUS='NEW')
          ISSNUM=0
          DO 1100 ISSGP=1,NUMISSGP
            DO 1102 ISS=1,NUMISS(ISSGP)
```

```
                 ISSNUM=ISSNUM+1
                 JSSNUM(ISS,ISSGP)=ISSNUM
1102       CONTINUE
1100    CONTINUE
        NUMTOTISS=ISSNUM
        NUMTOTVAR=ISSNUM+NUMCSQ
        DO 1104 ISAMP=1,NUMSAMP
           DO 1106 ISSGP=1,NUMISSGP
              DO 1108 ISS=1,NUMISS(ISSGP)
                 ISSNUM=JSSNUM(ISS,ISSGP)
                 IF(NOMINAL(ISS,ISSGP))THEN
                 XOUT(ISSNUM)=LVL(ISSGP,ISS,ISAMP)
                 ELSE
                 LEVEL=LVL(ISSGP,ISS,ISAMP)
                 XOUT(ISSNUM)=SLVL(ISS,ISSGP,LEVEL)
                 ENDIF
1108          CONTINUE
1106       CONTINUE
           DO 1110 ICSQ=1,NUMCSQ
              IVAR=NUMTOTISS+ICSQ
              XOUT(IVAR)=R(ISAMP,ICSQ)
1110       CONTINUE
           WRITE(4,1120)(XOUT(IVAR),IVAR=1,NUMTOTVAR)
1120       FORMAT(1P8E9.2)
1104    CONTINUE
        CLOSE(UNIT=4)
        END IF
        IF(BASE.AND.IOPT(10))CALL CCDF
        IF(BASE.AND.(.NOT.IOPT(3)))RETURN
        IF(.NOT.BASE.AND.(.NOT.IOPT(4)))RETURN
C       FIND TOTAL NUMBER OF LEVELS FOR ALL ISSUES
        NUMTOTLVL=0
        DO 1 ISSGP=1,NUMISSGP
           NUMTOTLVL=NUMTOTLVL+NUMISS(ISSGP)
1       CONTINUE
        DO 3 II=1,NUMTOTLVL
           ILVL(II)=II
3       CONTINUE
        IF(NUMSEQVECT.LT.2)THEN
           FMN=FMD(1)
           F05=FMD(1)
           F50=FMD(1)
           F95=FMD(1)
           FVAR=0.
        ELSE
C       SORT MELTDOWN FREQUENCIES IN ASCENDING ORDER
C       FIRST, INITIALIZE SORTED ARRAYS
        DO 100 I=1,NUMSAMP
           FMS(I)=FMD(I)
           PFMS(I)=PROB(I)
100     CONTINUE
C         NOW PERFORM A "BUBBLE SORT" ON FMD
```

```
      CALL SORT(FMS,PFMS,NUMSAMP)
C      FREQUENCIES AND PROBABILITIES ARE NOW SORTED IN
C      ORDER OF ASCENDING FREQUENCIES.
C
C      NOW DETERMINE CUMULATIVE PROBABILITY DISTRIBUTION
      CUMFMD(1)=PFMS(1)
      DO 130 I=2,NUMSAMP
        CUMFMD(I)=CUMFMD(I-1)+PFMS(I)
130   CONTINUE
C      NOW FIND 5-TH, 50-TH, & 95-TH PERCENTILES.
      CALL PCTILE(CUMFMD,FMS,.05,F05,NUMSAMP)
      CALL PCTILE(CUMFMD,FMS,.50,F50,NUMSAMP)
      CALL PCTILE(CUMFMD,FMS,.95,F95,NUMSAMP)
C      NOW FIND WEIGHTED MEANS AND VARIANCES
      SUM1=0.0
      SUM3=0.0
      DO 140 I=1,NUMSAMP
        SUM1=SUM1+FMD(I)
        SUM3=SUM3+FMD(I)**2
140   CONTINUE
      FMN=SUM1/NUMSAMP
      FVAR=(NUMSAMP*SUM3-SUM1**2)/NUMSAMP/(NUMSAMP-1)
C      WRITE MELTDOWN FREQUENCIES, SORTED
      WRITE (1,910)
910   FORMAT(1H1,5X,'SORTED MELTDOWN FREQUENCIES'/
     $ 5X,'PROBABILITY',6X,'CUM. PROB.',7X,'FREQUENCY')
      WRITE(1,1030)(PFMS(I),CUMFMD(I),FMS(I),
     $ I=1,NUMSAMP)
1030  FORMAT(3(5X,1PE12.3))
      WRITE(1,1040)FMN,FVAR
      WRITE(1,1060)F05,F50,F95
      ENDIF
C      STEP THROUGH CONSEQUENCES.
      DO 10 ICSQ=1,NUMCSQ
C      RISK AND PROBABILITIES WILL BE SORTED IN ORDER OF
C      ASCENDING RISK.  FIRST, SET THE SORTED ARRAY.
        DO 20 I=1,NUMSAMP
          RX(I)=R(I,ICSQ)
          PX(I)=PROB(I)
20      CONTINUE
C      NOW PERFORM A "BUBBLE SORT" ON RISK.
      CALL SORT(RX,PX,NUMSAMP)
      DO 25 I=1,NUMSAMP
        RS(I,ICSQ)=RX(I)
        PS(I,ICSQ)=PX(I)
25    CONTINUE
      DO27 I=1,NUMSAMP
        RX(I)=R(I,ICSQ)
        XX(I)=I
27    CONTINUE
      CALL SORT(RX,XX,NUMSAMP)
C      RISKS AND PROBABILITIES ARE NOW SORTED IN ORDER OF
```

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C     ASCENDING RISK.
C     NOW COMPUTE CUMULATIVE PROBABILITY DISTRIBUTION.
C     ASSUME THAT RISK IS UNIFORMLY DISTRIBUTED, HENCE
C     CUMULATIVE DISTRIBUTION COMMENCES WITH (P1)/2.
C
      CUM(1)=PX(1)/2.
      DO 50 I=2,NUMSAMP
        CUM(I)=CUM(I-1)+(PX(I)+PX(I-1))/2.
50    CONTINUE
C     FIND MEANS AND VARIANCES.
      SUM1=0.0
      SUM3=0.0
      DO 60 I=1,NUMSAMP
        SUM1=SUM1+R(I,ICSQ)
        SUM3=SUM3+R(I,ICSQ)**2
60    CONTINUE
      RMN=SUM1/NUMSAMP
      VAR=(NUMSAMP*SUM3-SUM1**2)/NUMSAMP/(NUMSAMP-1)
C     FIND 5-TH, 50-TH, AND 95-TH PERCENTILES.
      CALL PCTILE(CUM,RX,.05,R05(ICSQ),NUMSAMP)
      CALL PCTILE(CUM,RX,.50,R50(ICSQ),NUMSAMP)
      CALL PCTILE(CUM,RX,.95,R95(ICSQ),NUMSAMP)
C     WRITE OUT ISSUE LEVELS FOR SORTED RISKS
      WRITE(1,915)NAMCSQ(ICSQ)
      WRITE(3,915)NAMCSQ(ICSQ)
      IF(BASE)THEN
        WRITE(1,936)NAMBAS
        WRITE(3,936)NAMBAS
      ELSE
        WRITE(1,937)NAMALT
        WRITE(3,937)NAMALT
      ENDIF
      WRITE(1,1325)
      WRITE(3,1325)
1325  FORMAT(5X,'RANKING OF EACH SAMPLE MEMBER,'
     $ ' IN ORDER OF INCREASING RISK'/
     $    1X,'OBS RANK',7X,'OBS NO.',7X,'RISK')
      DO 1620 I=1,NUMSAMP
        IS=XX(I)
        WRITE(1,1625)I,IS,RX(I)
        WRITE(3,1625)I,IS,RX(I)
1625  FORMAT(3X,I3,11X,I3,5X,1PE12.3)
1620  CONTINUE
      WRITE(1,1040)RMN,VAR
1040  FORMAT(//5X,'MEAN = ',1PE12.3,5X,
     $ 'VARIANCE = ',1PE12.3)
      WRITE(1,1060)R05(ICSQ),R50(ICSQ),R95(ICSQ)
1060  FORMAT(/5X,'PERCENTILES :'/
     $ 10X,'5-TH = ',1PE12.3,'  50-TH = ',1PE12.3,
     $ '  95-TH = ',1PE12.3)
      RMNLO=RMN*SEQMULLO
      RMNHI=RMN*SEQMULHI
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            R05LO=R05(ICSQ)*SEQMULLO
            R95HI=R95(ICSQ)*SEQMULHI
            WRITE(3,1380)R05LO,RMNLO,R05(ICSQ),RMN,R95(ICSQ),RMNHI,R95HI
1380    FORMAT(20X,'5-TH PCTILE',2X,'MEAN',8X,'95-TH PCTILE'/
       $           5X,'LOW DATA',7X,2(1PE12.3)/
       $           5X,'NOM. DATA',6X,3(1PE12.3)/
       $       5X,'HIGH DATA',18X,2(1PE12.3)//)
C       HOW MANY SAMPLE MEMBERS ARE ABOVE THE LOGARITHMIC MIDPOINT?
        RMIN=1.E20
        RMAX=-1.E20
        NTOT=0
        DO 9100 ISAMP=1,NUMSAMP
           IF(R(ISAMP,ICSQ).LE.0.)GOTO 9100
           RMAX=MAX(R(ISAMP,ICSQ),RMAX)
           RMIN=MIN(R(ISAMP,ICSQ),RMIN)
           NTOT=NTOT+1
9100    CONTINUE
        RLOGMID=SQRT(RMAX*RMIN)
        NPLUS=0
        DO 9150 ISAMP=1,NUMSAMP
           IF(R(ISAMP,ICSQ).GT.RLOGMID)NPLUS=NPLUS+1
9150    CONTINUE
C       THE NUMBER OF (NONZERO) POINTS BELOW THE MIDDLE
        NMINUS=NTOT-NPLUS
        XNT=NTOT
        XNP=NPLUS
        CHISQ=4.*(XNT/2.-XNP)**2/XNT
C       IS THE DIFFERENCE IN NUMBER OF POINTS ABOVE AND BELOW THE
C       LOG MID-POINT SIGNIFICANT?
        CHICR05=3.84146
        CHICR01=6.6349
        WRITE(1,2760)RLOGMID,NPLUS,NMINUS,CHISQ
2760    FORMAT(5X,'LOGARITHMIC MIDPOINT (OF POINTS > 0.) = ',
       $           1PE12.3/5X,'NUMBER ABOVE MIDPOINT =',I3/
       $        5X,'NUMBER BELOW MIDPOINT = ',I3/
       $        5X,'CHI-SQUARED(1) = ',1PE12.3)
        IF(CHISQ.GE.CHICR05)THEN
              IF(CHISQ.GE.CHICR01)THEN
                    WRITE(1,2765)
              ELSE
                    WRITE(1,2766)
              ENDIF
        ELSE
              WRITE(1,2768)
        ENDIF
2765    FORMAT(5X,'REJECT NULL (p < .01)')
2766    FORMAT(5X,'REJECT NULL (p < .05)')
2768    FORMAT(5X,'DO NOT REJECT NULL (p > .05)')
C       WRITE OUT FRACTIONAL CONTRIBUTION OF EACH SEQUENCE TO
C       MEAN RISK
        WRITE(1,915)NAMCSQ(ICSQ)
915     FORMAT(1H1,4X,'CONSEQUENCE MEASURE:'/5X,A80/)
```

```
      IF(BASE)THEN
         WRITE(1,936)NAMBAS
      ELSE
         WRITE(1,937)NAMALT
      ENDIF
      WRITE(1,920)
920   FORMAT(5X,'FRACTIONAL CONTRIBUTION OF EACH SEQUENCE '
     $  ,'TO MEAN RISK'/20X,'SEQUENCE',12X,'CONTRIBUTION')
      DO 200 ISEQ=1,NUMSEQ
         RSEQ(ICSQ,ISEQ)=RSEQ(ICSQ,ISEQ)/SUM1
         WRITE(1,930)NAMSEQ(ISEQ),RSEQ(ICSQ,ISEQ)
930   FORMAT(20X,A20,F12.4)
200   CONTINUE
C     WRITE OUT FRACTIONAL CONTRIBUTIONS OF EACH CFM TO
C     MEAN RISK
      WRITE(1,935)NAMCSQ(ICSQ)
      IF(BASE)THEN
         WRITE(1,936)NAMBAS
      ELSE
         WRITE(1,937)NAMALT
      ENDIF
      WRITE(1,9401)
9401  FORMAT(5X,'FRACTIONAL CONTRIBUTION OF EACH NONZERO BIN TO'
     $       ' MEAN RISK'/20X,'BIN',17X,'CONTRIBUTION')
      DO 251 ICFM=1,NUMCFM
         RCFM(ICSQ,ICFM)=RCFM(ICSQ,ICFM)/SUM1
         CODEX=CODE(ICFM)
         IF(RCFM(ICSQ,ICFM).GE.5.E-05)
     $       WRITE(1,931)CODEX(1:LCODE),RCFM(ICSQ,ICFM)
931      FORMAT(20X,A,14X,F12.4)
251   CONTINUE
C
C     WRITE OUT FRACTIONAL CONTRIBUTIONS OF EACH RELEASE TO
C     MEAN RISK
      WRITE(1,935)NAMCSQ(ICSQ)
935   FORMAT(1H1,4X,'CONSEQUENCE MEASURE:'/5X,A80/)
      IF(BASE)THEN
         WRITE(1,936)NAMBAS
      ELSE
         WRITE(1,937)NAMALT
      ENDIF
936.  FORMAT(5X,'BASE CASE :'/5X,A80)
937   FORMAT(5X,'SAFETY OPTION :'/5X,A80)
      WRITE(1,940)
940   FORMAT(5X,'FRACTIONAL CONTRIBUTIONS OF EACH RELEASE',
     $        ' TO MEAN RISK'/
     $      20X,'RELEASE',13X,'CONTRIBUTION')
      DO 250 IREL=1,NUMREL
         RREL(ICSQ,IREL)=RREL(ICSQ,IREL)/SUM1
         WRITE(1,930)NAMREL(IREL),RREL(ICSQ,IREL)
250   CONTINUE
C     FIND SENSITIVITY OF RISK TO EACH ISSUE
```

```
      WRITE(3,6990)NAMCSQ(ICSQ)
      WRITE(1,6990)NAMCSQ(ICSQ)
6990  FORMAT(1H1,4X,'CONSEQUENCE MEASURE:'/5X,A80/
     $         5X,'SENSITIVITY OF RISK TO ISSUES'/
     $         5X,'DISTRIBUTION OF RISK AT EACH LEVEL OF EACH ISSUE')
      IF(BASE)THEN
        WRITE(1,936)NAMBAS
        WRITE(3,936)NAMBAS
      ELSE
        WRITE(1,937)NAMALT
        WRITE(3,937)NAMALT
      ENDIF
      WRITE(1,7000)
7000  FORMAT(4X,'GP',1X,'ISS',1X,'LVL',1X,'NUM',6X,'5%',
     $         10X,'50%',9X,'MEAN',8X,'95%',6X,'R**2',3X,'F',6X,'DF',
     $         5X,'SIGNIF.')
      WRITE(3,7001)
7001  FORMAT(4X,'GP',1X,'ISS',1X,'LVL',6X,'5%',10X,'MEAN',
     $         8X,'95%')
      DO 500 ISSGP=1,NUMISSGP
      DO 510 ISS=1,NUMISS(ISSGP)
        GOFRED=.TRUE.
        IF(NOMINAL(ISS,ISSGP))THEN
C     COMPUTE MEAN RISK FOR EACH LEVEL, FOR NOMINAL VARIABLES
          DO 620 LEVEL=1,NUMLVL(ISS,ISSGP)
          XLVL(LEVEL)=LEVEL
          NUMSENS=0
          DO 630 ISAMP=1,NUMSAMP
            IF(LVL(ISSGP,ISS,ISAMP).NE.LEVEL)GOTO 630
            NUMSENS=NUMSENS+1
630       CONTINUE
            IF(NUMSENS.EQ.0) GOFRED=.FALSE.
620     CONTINUE
        ENDIF
C     SET UP REGRESSION MATRIX
C     THERE ARE NUMLVL-1 EQUATIONS FOR THE NUMLVL TREATMENT LEVELS,
C     FOR NOMINAL VARIABLES.  THERE ARE NUMSAMP SUBJECTS.
C     THE TREATMENT LEVELS ARE REPRESENTED BY DUMMY VARIABLES
C     ZERO FOR ANY DUMMY VARIABLE MEANS "NOT AT THIS LEVEL"
C     ZERO FOR ALL DUMMIES MEANS THE HIGHEST LEVEL (NUMLVL)
C     FOR RATIO VARIABLES, THERE IS ONLY ONE EQUATION;
C     THE INDEPENDENT VARIABLE IS THE VALUE OF THE PHYSICAL
C     QUANTITY ASSOCIATED WITH THE ISSUE.
      IF(NOMINAL(ISS,ISSGP))THEN
      NE=NUMLVL(ISS,ISSGP)-1
      DO 650 ISAMP=1,NUMSAMP
          DO 660 LEVEL=1,NE
            IRANK=XLVL(LEVEL)
            IF(LVL(ISSGP,ISS,ISAMP).EQ.IRANK)THEN
                Y(LEVEL,ISAMP)=1.0
            ELSE
                Y(LEVEL,ISAMP)=0.0
```

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            ENDIF
660         CONTINUE
            DO 655 KSAMP=1,NUMSAMP
              IF(XX(KSAMP).EQ.ISAMP)THEN
                RANK=KSAMP
                GOTO 657
              ENDIF
655         CONTINUE
657         Y(NE+1,ISAMP)=RANK
650    CONTINUE
C      NOW SET UP THE REGRESSION MATRIX FOR RATIO OR INTERVAL
C      VARIABLES.
       ELSE
         NE=1
         IF(NUMLVL(ISS,ISSGP).GT.1)GOTO 6821
           GOFRED=.FALSE.
           GOTO 6822
6821     DO 682 LEVEL=1,NUMLVL(ISS,ISSGP)
           NUMSENS=0
           DO 683 ISAMP=1,NUMSAMP
             IF(LVL(ISSGP,ISS,ISAMP).NE.LEVEL)GOTO 683
             NUMSENS=NUMSENS+1
683        CONTINUE
682      CONTINUE
           DO 651 ISAMP=1,NUMSAMP
             LEVEL=LVL(ISSGP,ISS,ISAMP)
             Y(1,ISAMP)=SLVL(ISS,ISSGP,LEVEL)
             YR=R(ISAMP,ICSQ)
             IF(YR.LE.0.)YR=1.E-20
             Y(NE+1,ISAMP)=LOG(YR)
651        CONTINUE
       ENDIF
6822   IF(GOFRED)THEN
         CALL FRESID(Y,NE,NUMSAMP,FRATIO,SIGNIF,KK,PEARS)
         SIGNIF=INT(100.*SIGNIF+.5)/100.
         RSQD=PEARS**2
       ELSE
         FRATIO=0.0
         SIGNIF=1.0
         KK=4
         PEARS=0.0
         RSQD=PEARS**2
       ENDIF
       IF(KK.EQ.1)THEN
           KWORD='ILL-CONDITIONED'
       ELSE IF(KK.EQ.2)THEN
           KWORD='ZERO COEFFICIENT'
       ELSE IF(KK.EQ.3)THEN
           KWORD='R IMPOSSIBLE'
       ELSE IF(KK.EQ.4)THEN
           KWORD='NO DATA'
       ELSE
```

```
              KWORD=' '
          ENDIF
          IF(SIGNIF.GT..05)THEN
                  SIGWORD='NS'
          ELSE IF(SIGNIF.GT..01)THEN
                  SIGWORD=' *'
          ELSE
                  SIGWORD='**'
          ENDIF
          NU1=NE
          NU2=NUMSAMP-NE-1
C         ORDER LEVELS BY MEAN RISK
          DO 5200 LEVEL=1,NUMLVL(ISS,ISSGP)
            NUMBER=0
            SUMR=0.
            DO 5300 ISAMP=1,NUMSAMP
              IF(LVL(ISSGP,ISS,ISAMP).NE.LEVEL)GOTO 5300
                SUMR=SUMR+R(ISAMP,ICSQ)
                NUMBER=NUMBER+1
5300        CONTINUE
            IF(NUMBER.GT.0)THEN
                SENSMN(LEVEL)=SUMR/NUMBER
            ELSE
                SENSMN(LEVEL)=0.
            ENDIF
            XLVL(LEVEL)=LEVEL
5200      CONTINUE
          CALL SORT(SENSMN,XLVL,NUMLVL(ISS,ISSGP))
          DO 5250 LEVEL=1,NUMLVL(ISS,ISSGP)
            LVLORD(LEVEL)=XLVL(LEVEL)
5250      CONTINUE
C         FIND AND PRINT OUT PERCENTILES AND MEANS FOR EACH ISSUE
              DO 520 NIVEL=1,NUMLVL(ISS,ISSGP)
                  LEVEL=LVLORD(NIVEL)
                  NUMSENS=0
                  SUMR=0.
                  SUMP=0.
                  SENSMIN=1.E20
                  SENSMAX=-1.E20
                  DO 530 ISAMP=1,NUMSAMP
                    IF(LVL(ISSGP,ISS,ISAMP).NE.LEVEL)
     $                   GOTO 530
                      NUMSENS=NUMSENS+1
                      RSENS(NUMSENS)=R(ISAMP,ICSQ)
                      PSENS(NUMSENS)=PROB(ISAMP)
                      SUMR=SUMR+RSENS(NUMSENS)
                      SUMP=SUMP+PSENS(NUMSENS)
                      SENSMIN=MIN(SENSMIN,R(ISAMP,ICSQ))
                      SENSMAX=MAX(SENSMAX,R(ISAMP,ICSQ))
530               CONTINUE
                  IF(NUMSENS.EQ.0)THEN
                      RSENS05=-999.
```

B.52

```
                RSENS50=-999.
                RSENS95=-999.
                SENSMN(LEVEL)=0.
                INTERP='#'
                INTERPHI='#'
                IF(NIVEL.EQ.1) WRITE(3,7011)ISSGP,ISS,LEVEL,RSENS05,INTERP,
     $                  SENSMN(LEVEL),RSENS95,INTERPHI,RSQD
                IF(NIVEL.EQ.1) WRITE(1,7020)ISSGP,ISS,LEVEL,NUMSENS,
     $                  SENSMN(LEVEL),RSQD,FRATIO,NU1,NU2,SIGNIF,SIGWORD,KWORD
                GOTO 520
            ENDIF
            SENSMN(LEVEL)=SUMR/NUMSENS
            DO 540 ISENS=1,NUMSENS
              PSENS(ISENS)=PSENS(ISENS)/SUMP
 540        CONTINUE
            CALL SORT(RSENS,PSENS,NUMSENS)
            IF (NUMSENS.LT.5)THEN
              RSENS05=-999.
              RSENS50=-999.
              RSENS95=-999.
            ELSE
              CUM(1)=PSENS(1)/2.
              DO 560 ISENS=2,NUMSENS
                CUM(ISENS)=CUM(ISENS-1)+(PSENS(ISENS)
     $                    +PSENS(ISENS-1))/2.
 560          CONTINUE
C     FIND 5-TH, 50-TH, AND 95-TH PERCENTILES
                CALL PCTILE(CUM,RSENS,.05,RSENS05,NUMSENS)
                CALL PCTILE(CUM,RSENS,.50,RSENS50,NUMSENS)
                CALL PCTILE(CUM,RSENS,.95,RSENS95,NUMSENS)
                INTERP=' '
                INTERPHI=' '
                IF(RSENS05.LT.RSENS(1))INTERP='#'
                IF(RSENS95.GT.RSENS(NUMSENS))INTERPHI='#'
                RSENS05=MAX(RSENS05,SENSMIN)
                RSENS95=MIN(RSENS95,SENSMAX)
            ENDIF
 8888       FORMAT(/3I5/(10(1PE12.3)))
 7011       FORMAT(2X,3I4,1PE12.3,A1,1PE12.3,1PE12.3,A1,1PE12.3)
              IF(NIVEL.EQ.1)THEN
                WRITE(3,7011)ISSGP,ISS,LEVEL,RSENS05,INTERP,
     $                  SENSMN(LEVEL),RSENS95,INTERPHI,RSQD
                IF(NUMSENS.GE.5)THEN
                  WRITE(1,7010)ISSGP,ISS,LEVEL,NUMSENS,
     $                    RSENS05,RSENS50,SENSMN(LEVEL),RSENS95,
     $                    RSQD,FRATIO,NU1,NU2,SIGNIF,SIGWORD,KWORD
                ELSE
                  WRITE(1,7020)ISSGP,ISS,LEVEL,NUMSENS,
     $                    SENSMN(LEVEL),RSQD,FRATIO,NU1,NU2,SIGNIF,
     $                    SIGWORD,KWORD
                ENDIF
              ELSE
```

```fortran
                  WRITE(3,7012)LEVEL,RSENS05,INTERP,
     $                      SENSMN(LEVEL),RSENS95,INTERPHI
7012              FORMAT(10X,I4,1PE12.3,A1,2(1PE12.3),A1)
                  IF(NUMSENS.GE.5)THEN
                     WRITE(1,7030)LEVEL,NUMSENS,RSENS05,
     $                      RSENS50,SENSMN(LEVEL),RSENS95
                  ELSE
                     WRITE(1,7040)LEVEL,NUMSENS,SENSMN(LEVEL)
                  ENDIF
               ENDIF
7010  FORMAT(2X,4I4,4E12.4,F7.2,F7.1,'(',I3,',',I3,')',F7.2,A2,A20)
7020  FORMAT(2X,4I4,'*********************',E12.4,
     $         '***********',F7.2,F7.1,'(',I3,',',I3,')',F7.2,A2,A20)
7030  FORMAT(10X,2I4,4E12.4)
7040  FORMAT(10X,2I4,'*********************',E12.4,
     $         '***********')
520       CONTINUE
510     CONTINUE
500   CONTINUE
      WRITE (1,7050)
7050  FORMAT(5X,'NS=NOT SIGNIFICANT, *=SIGNIFICANT (P<.05),'
     $         ' **=SIGNIFICANT (P<.01)')
      IF(IOPT(8))CALL FCHISQ(ICSQ)
10    CONTINUE
      IF(IOPT(9))CALL DETANAL
      RETURN
      END
      SUBROUTINE PCTILE(P,X,PCT,XPCT,N)
C     THIS SUBROUTINE COMPUTES THE PCT-TH PERCENTILE OF AN
C     ORDERED SET OF VALUES.
C*******************************************************************
      INCLUDE 'GENPARAM2.FOR'
C*******************************************************************
      DIMENSION P(3*MAXSAMP),X(3*MAXSAMP)
C     P = CUMULATIVE PROBABILITY
C     X = VALUE

C     DETERMINE IF 1-ST PROB. > PCT
      IF (P(1).GT.PCT) GOTO 100
C     DETERMINE IF LAST PROB. < PCT
      IF (P(N).LT.PCT) GOTO 200
C     FIND PROB. JUST > PCT
      DO 10 I=2,N
         IF(P(I).GT.PCT) GOTO 15
10    CONTINUE
      I=N
C     ASSUME LOGARITHMICALLY DISTRIBUTED VARIABLES IF >0.,
C     OTHERWISE, LINEARLY DISTRIBUTED.
15    IF(X(I).GT.0..AND.X(I-1).GT.0.)THEN
      X1=LOG(X(I-1))
      X2=LOG(X(I))
      IF(P(I).NE.P(I-1))THEN
```

```fortran
      XN=X1+(X2-X1)*(PCT-P(I-1))/(P(I)-P(I-1))
      ELSE
      XN=X1
      ENDIF
      XPCT=EXP(XN)
      ELSE
      X1=X(I-1)
      X2=X(I)
      XPCT=X1+(X2-X1)*(PCT-P(I-1))/(P(I)-P(I-1))
      ENDIF
      RETURN
C     1-ST PROB. > PCT; EXTRAPOLATE BACKWARDS
100   IF(X(1).GT.0..AND.X(2).GT.0.)THEN
C     ASSUME LOG NORMAL DISTRIBUTION
C     FIRST FIND Z-VALUES CORRESPONDING TO P(1) & P(2)
      CALL NORMINV(P(1),Z1)
      CALL NORMINV(P(2),Z2)
C     FIND MEAN & SD APPROPRIATE FOR THIS DISTR.
      SD=LOG(X(1)/X(2))/(Z1-Z2)
      XMN=LOG(X(1))-Z1*SD
C     FIND Z-VALUE CORRESPONDING TO PCT
      CALL NORMINV(PCT,ZPCT)
      XN=XMN+ZPCT*SD
      XPCT=EXP(XN)
      RETURN
      ELSE
C     VALUES <0., ASSUME NORMAL DISTRIBUTION
      CALL NORMINV(P(1),Z1)
      CALL NORMINV(P(2),Z2)
C     FIND MEAN AND SD APPROPRIATE FOR THIS DISTR.
      SD=(X(1)-X(2))/(Z1-Z2)
      XMN=X(1)-Z1*SD
C     FIND Z VALUE CORRESPONDING TO PCT
      CALL NORMINV(PCT,ZPCT)
      XPCT=XMN+ZPCT*SD
        RETURN
      ENDIF
C     LAST PROB. > PCT; EXTRAPOLATE FORWARDS
200   IF(X(N).GT.0..AND.X(N-1).GT.0.)THEN
C     ASSUME LOG NORMAL DISTRIBUTION
C     FIND Z-VALUES CORRESPONDING TO P(N) & P(N-1)
      CALL NORMINV(P(N),ZN)
      CALL NORMINV(P(N-1),ZNM1)
      SD=LOG(X(N)/X(N-1))/(ZN-ZNM1)
      XMN=LOG(X(N))-ZN*SD
C     FIND Z-VALUE CORRESONDING TO PCT
      CALL NORMINV(PCT,ZPCT)
      XN=XMN+ZPCT*SD
      XPCT=EXP(XN)
        RETURN
      ELSE
C     ONE VALUE <0., ASSUME NORMAL DISTR.
```

```
C       FIND Z-VALUES CORRESPONDING TO P(N) & P(N-1)
        CALL NORMINV(P(N),ZN)
        CALL NORMINV(P(N-1),ZNM1)
C       FIND MEAN AND SD APPROPRIATE FOR THIS DISTR.
        SD=(X(N)-X(N-1))/(ZN-ZNM1)
        ZMN=X(N)-ZN*SD
        CALL NORMINV(PCT,ZPCT)
        XPCT=XMN+ZPCT*SD
          RETURN
        ENDIF
        END
        SUBROUTINE NORMINV(P,Z)
C       INVERSE NORMAL PROBABILITY FUNCTION
C       REFERENCE: ABRAMOWITZ & STEGUN EQN. 26.2.22
        IF(P.GT..5)THEN
              Q=1.-P
        ELSE
              Q=P
        ENDIF
        T=SQRT(LOG(1./Q**2))
        Z=T-(2.30753*T+.04481*T**2)/(1.+.99229*T+
     $        .04481*T**2)
        IF(P.LT..5)Z=-Z
        RETURN
        END
        SUBROUTINE ONSITCOS(DISCAV,BASE)
C        A subroutine to calculate on-site costs of a melt-down
C        accident.
C
c        DISCAV: Discounted average cost
C********************************************************************
C       CAUTION!! HAS EVERYTHING IN THE PARAMETER, EXPLANATORY, AND    *
C       COMMON STATEMENTS OF THE MAIN PROGRAM BEEN PUT INTO            *
C       "GENPARAM2.FOR", "EXPLAN2.FOR", AND "GENCOM2.FOR"?             *
C********************************************************************
C
        INCLUDE 'GENPARAM2.FOR'
        INCLUDE 'EXPLAN2.FOR'
        INCLUDE 'GENCOM2.FOR'
        DIMENSION DISCAV(3)
C       JBLT: Year plant started on-line.
C       JUSLIF: Estimated number of years of useful life.
C       JPRES: Present year
C       PMWE: Plant power (MWe)
C       CAPF: Average plant capacity factor, %
C       DISCR: discount rate
C       PPCI: Power cost differential
C       CPKWI: Cost per kilowatt installed (plant cost)
C       CCUP: Cost of cleanup
C       CDEC: cost of decommissioning
C       OSHC: on-site health costs
C       ESCR: fossil fuel cost escalation rate
```

B.56

```
      INTEGER JREM,JBLT,JUSLIF,JPRES,JRAC,JACC,JREP,JCAP
      REAL PPCI,CPKWI,CCUP,CDEC,OSHC,PMWE,CAPF,DISCR,ESCR,    .
     $ CRPAC,CAPAC,CCPYR,C1TIM,CTOTAC,CTOTPR,SDISC,SNDIS,
     $ DISCAV,UDCAV,COSMX
C     ***************************************************
C
      JREM = JBLT+JUSLIF-JPRES
      COSMX=0.
C     Loop over cost variables (opt., cent., pess.)
      DO 50 JC=1,3
C      Total remaining useful life
      SDISC=0.
      SNDIS=0.
      IF(BASE)AVCRP=0.
      IF(BASE)AVCAP=0.
C
C       Loop over remaining useful life
      DO 10 JACC=1,JREM
C      Remaining useful life at time of accident
        JRAC=JREM-JACC
C      Time for replacement power           .
        IF(JRAC.LT.10)THEN
          JREP=JRAC
        ELSE
          JREP=10.
        ENDIF
C      Discounted cost, at time of accident, of replacement
C      power
        IF(DISCR.NE.ESCR)THEN
          CRPAC=PMWE*CAPF*PPCI(JC)*(1.-EXP(-(DISCR-ESCR)
     $          *JREP))/(DISCR-ESCR)/65
        ELSE
          CRPAC=PMWE*CAPF*PPCI(JC)*JREP/65
        ENDIF    .
        IF(BASE)
     $  AVCRP=AVCRP+CRPAC*EXP(-DISCR*JACC)
C      Discounted cost, at time of accident, of capital
C      amortization.
        IF(JRAC.LE.10)THEN
          CAPAC=0.
        ELSE
c      Capital cost per year
          CCPYR=1000*CPKWI(JC)*PMWE/JUSLIF
C      Integrated capital cost
          CAPAC=CCPYR*(EXP(-DISCR*JREP)
     $          -EXP(-DISCR*JRAC))/DISCR
        ENDIF
        IF(BASE)
     $   AVCAP=AVCAP+CAPAC*EXP(-DISCR*JACC)
C      One time costs; cleanup, decommissioning, and
C      on-site health costs
        C1TIM=CCUP(JC)+CDEC(JC)+OSHC(JC)
```

B.57

```
C        Total costs at time of accident
         CTOTAC=CRPAC+CAPAC+C1TIM
         IF(CTOTAC.GT.COSMX)COSMX=CTOTAC
         CTOTPR=CTOTAC*EXP(-DISCR*JACC)
         SDISC=SDISC+CTOTPR
10     CONTINUE
C      Average costs
       DISCAV(JC)=SDISC/JREM
50     CONTINUE
       RETURN
       END
       SUBROUTINE SORT(Y,P,N)
C      SORTS VALUES AND PROBABILITIES IN ORDER OF ASCENDING VALUE.
C*************************************************************************
       INCLUDE 'GENPARAM2.FOR'
C*************************************************************************
       DIMENSION Y(3*MAXSAMP), P(3*MAXSAMP)
       LOGICAL PP
C      PERFORM "BUBBLE SORT" ON VALUE
10     PP=.FALSE.
       DO 5 I=2,N
            IF(Y(I).LT.Y(I-1))THEN
C      PAIR NOT IN ORDER; REVERSE THEM.
                 TEMP=Y(I-1)
                 Y(I-1)=Y(I)
                 Y(I)=TEMP
                 TEMP=P(I-1)
                 P(I-1)=P(I)
                 P(I)=TEMP
C      SORT WASN'T COMPLETED
                 PP=.TRUE.
            ENDIF
5      CONTINUE
C      IS THE SORT COMPLETED?
       IF(PP)GOTO 10
C      SORT COMPLETED
       RETURN
       END
       SUBROUTINE OUTCOST(BASE,DISCAV)
C      CALCULATES COST OF MELTDOWN ACCIDENTS.
       INCLUDE 'GENPARAM2.FOR'
       INCLUDE 'EXPLAN2.FOR'
       INCLUDE 'GENCOM2.FOR'
       DIMENSION   C1(MAXSAMP),       C2(MAXSAMP),
      $                    P1CS(MAXSAMP),    P2CS(MAXSAMP),
      $                    CUM1(MAXSAMP),    CUM2(MAXSAMP),
      $                    ONSC(3*MAXSAMP),PONSC(3*MAXSAMP),
      $                    CUMONSC(3*MAXSAMP),DISCAV(3)
C      COMPUTE TOTAL OFFSITE COSTS :
C      (A) (PROP DAM) + (1E6*EARLY FAT) + (1E5*ILLNESS) + (1E5*CANCER)
C      (B) 1E3*POP DOSE
       IF(BASE.AND.(.NOT.IOPT(3)))RETURN
```

```fortran
            SUMC1=0
            SUMC2=0
            DO 10 ISAMP=1,NUMSAMP
              C1(ISAMP)=R(ISAMP,KCOS)+1.E6*R(ISAMP,KFAT)+1.E5*R(ISAMP,KILL)
         $          +1.E5*R(ISAMP,KLAT)
              C2(ISAMP)=1.E3*R(ISAMP,KDOS)
              P1CS(ISAMP)=PROB(ISAMP)
              P2CS(ISAMP)=PROB(ISAMP)
              SUM1=SUM1+C1(ISAMP)
              SUM2=SUM2+C2(ISAMP)
   10       CONTINUE
            C1MN=SUM1/NUMSAMP
            C2MN=SUM2/ISAMP
            CALL SORT(C1,P1CS,NUMSAMP)
            CALL SORT(C2,P2CS,NUMSAMP)
            CUM1(1)=P1CS(1)/2.
            CUM2(1)=P2CS(1)/2.
            DO 20 ISAMP=2,NUMSAMP
              CUM1(ISAMP)=CUM1(ISAMP-1)+(P1CS(ISAMP)
         $        +P1CS(ISAMP-1))/2.
              CUM2(ISAMP)=CUM2(ISAMP-1)+(P2CS(ISAMP)
         $          +P2CS(ISAMP-1))/2.
   20       CONTINUE
   C        FIND PERCENTILES
            CALL PCTILE(CUM1,C1,.05,C105,NUMSAMP)
            CALL PCTILE(CUM1,C1,.50,C150,NUMSAMP)
            CALL PCTILE(CUM1,C1,.95,C195,NUMSAMP)
            CALL PCTILE(CUM2,C2,.05,C205,NUMSAMP)
            CALL PCTILE(CUM2,C2,.50,C250,NUMSAMP)
            CALL PCTILE(CUM2,C2,.95,C295,NUMSAMP)
            WRITE(1,1000)C1MN,C105,C150,C195
 1000       FORMAT(1H1,5X,'COSTS OF MELTDOWN ACCIDENTS'/
         $          5X,'ANNUAL OFFSITE COSTS AS THE SUM OF :'/
         $          5X,'PROP. DAM., 1E6*EARLY FAT., 1.E5*ILLNESS,'
         $        AND 1.E5*LATENT CANCERS'/
         $          5X,'MEAN = ',1PE12.3/5X,'PERCENTILES : '/
         $          10X,'5-TH = ',1PE12.3,5X,'50-TH = ',1PE12.3,5X,
         $          '95-TH = ',1PE12.3)
            WRITE(1,1010)C2MN,C205,C250,C295
 1010       FORMAT(/5X,'ANNUAL OFFSITE COST AS 1E3*POP. DOSE'/
         $          5X,'MEAN = ',1PE12.3/5X,'PERCENTILES : '/
         $          10X,'5-TH = ',1PE12.3,5X,'50-TH = ',1PE12.3;5X,
         $          '95-TH = ',1PE12.3)
   C      COMPUTE AVERAGE ANNUAL ONSITE COSTS.  COST INPUTS HAVE
   C      HIGH, MIDDLE, AND LOW VALUES, EACH OF WHICH IS
   C      EQUALLY WEIGHTED.  EACH AVERAGE COST (GIVEN CORE MELT)
   C      IS MULTIPLIED BY THE CORE MELT FREQUENCY FOR EACH
   C      SAMPLE MEMBER.
   C
   C      FIRST, FIND AVERAGE ONSITE COST, GIVEN CORE MELT
            CALL ONSITCOS(DISCAV,BASE)
            NUMCOST=3*NUMSAMP
```

B.59

```fortran
            SUMONSC=0.
            DO 30 JCOST=1,3
              DO 35 ISAMP=1,NUMSAMP
                KCOST=(JCOST-1)*NUMSAMP+ISAMP
                ONSC(KCOST)=DISCAV(JCOST)*FMD(ISAMP)
                SUMONSC=SUMONSC+ONSC(KCOST)
                PONSC(KCOST)=PROB(ISAMP)/3.
35            CONTINUE
30          CONTINUE
            ONSCMN=SUMONSC/NUMCOST
            CALL SORT(ONSC,PONSC,NUMCOST)
            CUMONSC(1)=PONSC(1)/2.
            DO 40 I=2,NUMCOST
              CUMONSC(I)=CUMONSC(I-1)+(PONSC(I)
     $               +PONSC(I-1))/2.
40          CONTINUE
            CALL PCTILE(CUMONSC,ONSC,.05,ONSC05,NUMCOST)
            CALL PCTILE(CUMONSC,ONSC,.50,ONSC50,NUMCOST)
            CALL PCTILE(CUMONSC,ONSC,.95,ONSC95,NUMCOST)
            WRITE(1,1020)ONSCMN,ONSC05,ONSC50,ONSC95
1020    FORMAT(/5X,'ANNUAL ONSITE COSTS :'/
     $         5X,'MEAN = ',1PE12.3/5X,'PERCENTILES : '/
     $         10X,'5-TH = ',1PE12.3,5X,'50-TH = ',1PE12.3,5X,
     $         '95-TH = ',1PE12.3)
C       TOTAL COSTS ARE THE SUM OF OFF AND ONSITE COSTS.
C       THE RANGE IS BASED ON THE RANGE OF ONSITE COSTS ONLY.
        C1TOTMN=C1MN+ONSCMN
        C2TOTMN=C2MN+ONSCMN
        C1TOT05=ONSC05+C1MN
        C2TOT05=ONSC05+C2MN
        C1TOT50=ONSC50+C1MN
        C2TOT50=ONSC50+C2MN
          C1TOT95=ONSC95+C1MN
        C2TOT95=ONSC95+C2MN
        WRITE(1,1040)C1TOTMN,C1TOT05,C1TOT50,C1TOT95
1040    FORMAT(//5X,'TOTAL COSTS BASED ON SUMMED OFFSITE COSTS'/
     $         5X,'MEAN = ',1PE12.3/5X,'PERCENTILES : '/
     $         10X,'5-TH = ',1PE12.3,5X,'50-TH = ',1PE12.3,5X,
     $         '95-TH = ',1PE12.3)
        WRITE(1,1050)C2TOTMN,C2TOT05,C2TOT50,C2TOT95
1050    FORMAT(/5X,'TOTAL COSTS BASED ON 1E3*POP. DOSE'/
     $         5X,'MEAN = ',1PE12.3/5X,'PERCENTILES : '/
     $         10X,'5-TH = ',1PE12.3,5X,'50-TH = ',1PE12.3,5X,
     $         '95-TH = ',1PE12.3)
        RETURN
        END
        SUBROUTINE FRESID(Y,NE,NO,F,Q,KK,RR)
        INCLUDE 'GENPARAM2.FOR'
        DIMENSION   Y(MAXLVL+1,MAXSAMP),
     $                  R(MAXLVL,MAXLVL),
     $                  B(MAXLVL,MAXLVL+1),
     $                  S(MAXLVL+1),T(MAXLVL+1),
```

```
      $                         C(MAXLVL+1,MAXLVL+1),YB(MAXLVL),
      $                         SD(MAXLVL),X(MAXLVL),XX(MAXLVL),
      $                         YP(MAXSAMP)
       DOUBLE PRECISION S,T,SP,TP,D1,D2
C      NE IS THE NUMBER OF EQUATIONS
C      NO IS THE NUMBER OF OBSERVATIONS
C
C
       KK=0
       MP=NE+1
       F=0.
       Q=1.0
       DO 10 J=1,MP
         S(J)=0.D0
         T(J)=0.D0
         DO 15 K=1,MP
           C(J,K)=0.
15       CONTINUE
         DO 20 I=1,NO
           S(J)=S(J)+Y(J,I)
           T(J)=T(J)+Y(J,I)**2
           DO 25 K=J,MP
             C(J,K)=C(J,K)+Y(J,I)*Y(K,I)
             C(K,J)=C(J,K)
25         CONTINUE
20       CONTINUE
         YB(J)=S(J)/NO
         SD(J)=SQRT((NO*T(J)-S(J)**2)/NO/(NO-1))
10     CONTINUE
       DO 30 J=1,NE
         DO 40 K=1,MP
           B(J,K)=0.
           IF(NO*T(J)-S(J)**2.EQ.0.)GOTO 40
           IF(NO*T(K)-S(K)**2.EQ.0.)GOTO 40
             B(J,K)=(NO*C(J,K)-S(J)*S(K))/
      $                SQRT((NO*T(J)-S(J)**2)*
      $                (NO*T(K)-S(K)**2))
40       CONTINUE
30     CONTINUE
       CALL SOLVE(NE,B,X,KK)
       IF(KK.GT.0)THEN
             F=0.
             Q=1.0
             RR=0.
       ENDIF
       A=YB(MP)
       DO 50 JJ=1,NE
         XX(JJ)=0.
         IF(SD(JJ).EQ.0.)GOTO 51
         XX(JJ)=X(JJ)*SD(MP)/SD(JJ)
51       A=A-XX(JJ)*YB(JJ)
50     CONTINUE
```

```fortran
      SP=0.D0
      TP=0.D0
      CC=0.0
      DO 60 I=1,NO
        YP(I)=A
          DO 70 J=1,NE
            YP(I)=YP(I)+XX(J)*Y(J,I)
70        CONTINUE
        SP=SP+YP(I)
        TP=TP+YP(I)**2
        CC=CC+Y(MP,I)*YP(I)
60    CONTINUE
      D1=NO*TP-SP*SP
      D2=NO*T(MP)-S(MP)*S(MP)
      IF(D1.LE.0.D0.OR.D2.LE.0.D0)THEN
          KK=3
          F=0.
          Q=1.0
          RR=0.
          RETURN
      ENDIF
      RR=(NO*CC-SP*S(MP))/SQRT(D1*D2)
      N1=NE
      N2=NO-NE-1
      IF((1.-RR**2)*N1.NE.0.)THEN
      F=RR**2*N2/(1.-RR**2)/N1
      CALL SIGNIF(F,N1,N2,Q)
      ELSE
      F=1000.
      Q=0.
      ENDIF
      RETURN
      END
      SUBROUTINE SOLVE(M,B,X,KK)
      INCLUDE 'GENPARAM2.FOR'
      DIMENSION B(MAXLVL,MAXLVL+1),X(MAXLVL)
      MP=M+1
      MM=M-1
      ZERO=1.E-30
      DO 10 I=1,MM
        BB=ABS(B(I,I))
        IB=I
        IP1=I+1
        DO 20 K=IP1,M
          IF(ABS(B(K,I)).LE.BB)GOTO 20
          BB=ABS(B(K,I))
          IB=K
20      CONTINUE
        IF(BB.LE.ZERO)GOTO 10
        DO 30 J=1,MP
          TE=B(I,J)
          B(I,J)=B(IB,J)
```

```
          B(IB,J)=TE
30      CONTINUE
        DO 40 J=IP1,M
          IF(B(J,I).EQ.0.)GOTO 40
          RT=B(I,I)/B(J,I)
          DO 50 L=I,MP
            B(J,L)=B(I,L)-RT*B(J,L)
50        CONTINUE
40      CONTINUE
10    CONTINUE
      IF((M.LE.0).OR.(B(M,M).EQ.0.))THEN
          KK=1
          RETURN
      ENDIF
      X(M)=B(M,MP)/B(M,M)
      DO 60 I=1,MM
        L=M-I
        IF(ABS(B(L,L)).LE.ZERO)THEN
          KK=2
          RETURN
        ENDIF
        X(L)=B(L,MP)/B(L,L)
        LP1=L+1
        DO 70 J=LP1,M
          X(L)=X(L)-B(L,J)*X(J)/B(L,L)
70      CONTINUE
60    CONTINUE
      RETURN
      END
      SUBROUTINE SIGNIF(F,N1,N2,Q)
C     PERCENTAGE POINTS OF THE F-DISTRIBUTION
C     REFERENCES TO --
C     ABRAMOWITZ, M. & STEGUN, I (1972).  HANDBOOK OF MATHEMATICAL
C     FUNCTIONS.  NEW YORK:  DOVER.
      LOGICAL O1,O2
      DATA PI/3.1415926536/
C     IF F=0., THEN Q=1.0
      IF(F.GT.0.01)GOTO 5
      Q=1.0
      RETURN
C     IF N1 OR N2 =1, USE STUDENT'S T
5     IF(N1.EQ.1)THEN
          T=SQRT(F)
          CALL STUDENTS(T,N2,A)
          Q=1.-A
          RETURN
      ELSE IF(N2.EQ.1)THEN
          T=SQRT(1./F)
          CALL STUDENTS(T,N1,A)
          Q=A
          RETURN
      ENDIF
```

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C       N1>1, N2>1
C       FIRST DETERMINE IF N1 AND N2 ARE ODD OR EVEN
        XN1=N1
        XN2=N2
        IF(XN1/2..NE.INT(XN1/2.))THEN
                O1=.TRUE.
        ELSE
                O1=.FALSE.
        ENDIF
        IF(XN2/2..NE.INT(XN2/2.))THEN
                O2=.TRUE.
        ELSE
                O2=.FALSE.
        ENDIF
C       N1 & N2 ARE BOTH ODD
C       A & S, EQN. 26.6.8
        IF(O1.AND.O2)THEN
                TH=ATAN(SQRT(XN1*F/XN2))
                T=SQRT(XN1*F)
                CALL STUDENTS(T,N2,A)
                SUM=1.0
                P1=1.0
                IEND=N1-3
                IF(IEND.EQ.0)GOTO 15
                DO 10 I=2,IEND,2
                        P1=P1*(N2+I-1)/(I+1)
                        SUM=SUM+P1*SIN(TH)**I
10              CONTINUE
15              X1=(XN2-1)/2.
                CALL FACT(X1,F1)
                BETA=2.*F1/SQRT(PI)*SIN(TH)*COS(TH)**N2*SUM
                Q=1.-A+BETA
                RETURN
C       O1 IS EVEN
        ELSE IF (.NOT.O1)THEN
C       A & S EQN. 26.6.6
                SUM=1.
                X=XN2/(XN2+XN1*F)
                IEND=N1-2
                IF(IEND.EQ.0)GOTO 25
                P1=1.0
                DO 20 I=2,IEND,2
                        P1=P1*(N1+N2-I)/I
                        SUM=SUM+P1*((1.-X)/X)**(I/2)
20              CONTINUE
25              Q=X**((XN1+XN2-2.)/2.)*SUM
                RETURN
C       O2 IS EVEN
C       A & S EQN. 26.6.7
        ELSE
                SUM=1.
                IEND=N2-2
```

```fortran
              P1=1.0
              X=XN2/(XN2+XN1*F)
              IF(IEND.EQ.0)GOTO 35
              DO 30 I=2,IEND,2
                      P1=P1*(N1+I-2)/I
                      SUM=SUM+P1*X**(I/2)
30            CONTINUE
35            Q=1.-(1.-X)**(XN1/2.)*SUM
              RETURN
      ENDIF
      END
      SUBROUTINE STUDENTS(T,N,A)
C     PERCENTAGE POINTS OF STUDENT'S T-DISTRIBUTION
      DATA PI/3.1415926536/
      IF(N.GT.30)GOTO 150
      XN=N
      TH=ATAN(T/SQRT(XN))
      IF(N.EQ.1)THEN
              A=2.*TH/PI
              RETURN
      ELSE
C     IS N ODD OR EVEN?
              IF(XN/2..EQ.INT(XN/2.))GOTO 80
C     N IS ODD
C     A & S 26.7.3
                      IEND=N-3
                      SUM=COS(TH)
                      IF(IEND.EQ.0)GOTO 15
                      P1=1.0
                      DO 10 I=2,IEND,2
                              P1=P1*I/(I+1)
                              SUM=SUM+P1*COS(TH)**(I+1)
10                    CONTINUE
15                    A=2./PI*(TH+SIN(TH)*SUM)
                      RETURN
C     N IS EVEN
C     A & S EQN. 26.7.4
80            IEND=N-1
              SUM=1.
              IF(IEND.EQ.0)GOTO 25
              P1=1.0
              DO 20 I=2,IEND,2
                      P1=P1*(I-1)/I
                      SUM=SUM+P1*COS(TH)**I
20            CONTINUE
25            A=SIN(TH)*SUM
              RETURN
      ENDIF
C     FOR N>30,USE NORMAL DISTRIBUTION
C     A & S EQN. 26.2.16
150   XN=N
      X=T*(1.-1./4./XN)/SQRT(1.+T**2/2./XN)
```

```
            FT=1./(1.+.33267*X)
            Z=.39894228*EXP(-X**2/2.)
            FF=.4361836*FT-.1201676*FT**2+.937298*FT**3
            PX=1.-Z*FF
            A=2*PX-1.
            RETURN
            END
            SUBROUTINE FACT(X,F)
C           RATIO OF [(X-1)/2]! TO [(X-2)/2]!, WHEN X IS ODD
C           G1O2=GAMMA(1/2)
            G1O2=1.7724538509
            IEND=X
            P=1.
            DO 10 I=1,IEND
                  P=P*I/(2*I-1)
10          CONTINUE
            N=INT(X+1.)
            F=P*2.**N/G1O2
                  RETURN
                  END
            SUBROUTINE RISKRED
C           THIS SUBROUTINE CALCULATES AND WRITES OUT DIFFERENTIAL
C           RISK, I.E., THE CHANGE IN RISK TO DUE A SAFETY OPTION.
C           NOTE: REDUCTION IN RISK IS POSITIVE!
            INCLUDE 'GENPARAM2.FOR'
            INCLUDE 'EXPLAN2.FOR'
            INCLUDE 'GENCOM2.FOR'
            DIMENSION DRS(MAXSAMP),PS(MAXSAMP),CUM(MAXSAMP),
          $          RSENS(MAXSAMP),PSENS(MAXSAMP),Y(MAXLVL,MAXSAMP),
          $          SENSMN(MAXLVL),XLVL(MAXLVL),DRX(MAXSAMP),XX(MAXSAMP),
          $          ILVL(MAXLVL),RRAT(MAXSAMP),PRAT(MAXSAMP)
           CHARACTER*20 SIGWORD
           CHARACTER*20 KWORD
           LOGICAL GOFRED
C           ******************************************************
C
           NUMTOTLVL=0
           DO 999 ISSGP=1,NUMISSGP
             NUMBISS=NUMISS(ISSGP)
             DO 998 ISS=1,NUMBISS
               NUMBLVL=NUMLVL(ISS,ISSGP)
               NUMTOTLVL=NUMTOTLV+NUMBLVL
998          CONTINUE
999        CONTINUE
C           LOOP THROUGH ALL CONSEQUENCE MEASURES
            DO 10 ICSQ=1,NUMCSQ
C           FIND DIFFERENTIAL RISK FOR EACH SAMPLE MEMBER.
C           FIND MEAN DIFFERENTIAL RISK
            IF(IOPT(5))THEN
               SUMDR=0.0
               DO 15 ISAMP=1,NUMSAMP
                 DR(ISAMP,ICSQ)=RB(ISAMP,ICSQ)-R(ISAMP,ICSQ)
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              DRS(ISAMP)=DR(ISAMP,ICSQ)
              PS(ISAMP)=PROB(ISAMP)
              SUMDR=SUMDR+DR(ISAMP,ICSQ)
15        CONTINUE
          DRMN=SUMDR/NUMSAMP
C     NOW SORT DIFFERENTIAL RISK IN ASCENDING ORDER
          CALL SORT(DRS,PS,NUMSAMP)
C     FIND CUMULATIVE PROBABILITIES
          CUM(1)=PS(1)/2.
          DO 20 I=2,NUMSAMP
             CUM(I)=CUM(I-1)+(PS(I)
     $               +PS(I-1))/2.
20        CONTINUE
C     FIND 5-TH, 50-TH, & 95-TH PERCENTILES.
          CALL PCTILE(CUM,DRS,.05,DR05,NUMSAMP)
          CALL PCTILE(CUM,DRS,.50,DR50,NUMSAMP)
          CALL PCTILE(CUM,DRS,.95,DR95,NUMSAMP)
          WRITE(1,1000)NAMCSQ(ICSQ),NAMALT
1000  FORMAT('1',4X,'CONSEQUENCE MEASURE:'/5X,A80/
     $       5X,'SAFETY OPTION:'/5X,A80//
     $       5X,'SORTED DIFFERENTIAL RISK'/
     $       5X,'PROBABILITY',6X,'CUM. PROB.',7X,'DIFFERENTIAL RISK')
          WRITE(1,1010)(PS(I),CUM(I),DRS(I),I=1,NUMSAMP)
1010  FORMAT(3(5X,1PE12.3))
          WRITE(1,1020)DRMN
1020  FORMAT(//5X,'MEAN = ',1PE12.3)
          WRITE(1,1030)DR05,DR50,DR95
1030  FORMAT(/5X,'PERCENTILES :'/
     $       10X,'5-TH = ',1PE12.3,'  50-TH = ', 1PE12.3,
     $   ' 95-TH = ',1PE12.3)
      ENDIF
      IF(IOPT(6))THEN
         SUMRR=0.0
         DO 150 ISAMP=1,NUMSAMP
            RRAT(ISAMP)=1.0
            IF(RB(ISAMP,ICSQ).NE.0.)RRAT(ISAMP)=R(ISAMP,ICSQ)/
     #               RB(ISAMP,ICSQ)
            PRAT(ISAMP)=PROB(ISAMP)
            SUMRR=SUMRR+RRAT(ISAMP)
150      CONTINUE
         RRMN=SUMRR/NUMSAMP
         CALL SORT(RRAT,PRAT,NUMSAMP)
         CUM(1)=PRAT(1)/2.
         DO 151 I=2,NUMSAMP
            CUM(I)=CUM(I-1)+(PRAT(I)+PRAT(I-1))/2.
151      CONTINUE
         CALL PCTILE(CUM,RRAT,.05,RR05,NUMSAMP)
         CALL PCTILE(CUM,RRAT,.50,RR50,NUMSAMP)
         CALL PCTILE(CUM,RRAT,.95,RR95,NUMSAMP)
         WRITE(1,152)NAMCSQ(ICSQ),NAMALT
152   FORMAT('1',4X,'CONSEQUENCE MEASURE:'/5X,A80/
     $       5X,'SAFETY OPTION:'/5X,A80//
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     $           5X,'SORTED RISK RATIO'/
     $           5X,'PROBABILITY',6X,'CUM. PROB.',7X,'RISK RATIO')
         WRITE(1,1010)(PRAT(I),CUM(I),RRAT(I),I=1,NUMSAMP)
         WRITE(1,1020)RRMN
         WRITE(1,1030)RR05,RR50,RR95
       END IF
10     CONTINUE
       RETURN
       END
       SUBROUTINE COSTBEN(DISCAV)
C      COST BENEFIT ANALYSIS OF SAFETY OPTIONS
       INCLUDE 'GENPARAM2.FOR'
       INCLUDE 'EXPLAN2.FOR'
       INCLUDE 'GENCOM2.FOR'
       DIMENSION VONSCOS(MAXCOSTIN*MAXSAMP),PONSC(MAXCOSTIN*MAXSAMP),
     $           CUM(MAXCOSTIN*MAXSAMP),VOFSC1(MAXSAMP),VOFSC2(MAXSAMP),
     $           POFF(MAXSAMP),TOTCOS1(MAXCOSTIN*MAXSAMP),
     $           TOTCOS2(MAXCOSTIN*MAXSAMP),PTOT(MAXCOSTIN*MAXSAMP),
     $           XI2(MAXCOSTIN),XI3(MAXCOSTIN),XI4(MAXCOSTIN),
     $           TOTIMP(MAXCOSTIN),DISCAV(MAXCOSTIN),DFMD(MAXSAMP),
     $           VTEMP(MAXSAMP),PQ(MAXSAMP)
       NUMCOST=MAXCOSTIN*NUMSAMP
C      FIND AVERTED ONSITE COST
       JREM=JBLT+JUSLIF-JPRES
C      FIND FACTORS OF AVERTED COSTS
       FACT=(1.-EXP(-DISCR*JREM))/DISCR/JREM
       FACTP=FACT*JREM
       DO 17 I=1,NUMSAMP
         DFMD(I)=FBMD(I)-FMD(I)
         PQ(I)=PROB(I)
17     CONTINUE
       DO 10 JCOST=1,MAXCOSTIN
         DO 15 ISAMP=1,NUMSAMP
           KCOST=(JCOST-1)*NUMSAMP+ISAMP
           VONSCOS(KCOST)=DISCAV(JCOST)*JREM*DFMD(ISAMP)
     $             +AVONSDOS*DFMD(ISAMP)*1000.*FACTP
           PONSC(KCOST)=PROB(ISAMP)/3.
15       CONTINUE
10     CONTINUE
       CALL SORT(VONSCOS,PONSC,NUMCOST)
       CALL SORT(DFMD,PQ,NUMSAMP)
       CUM(1)=PONSC(1)/2.
       DO 20 I=2,NUMCOST
         CUM(I)=CUM(I-1)+PONSC(I)
20     CONTINUE
C      FIND 5TH, 50TH, & 95TH PERCENTILES
       CALL PCTILE(CUM,VONSCOS,.05,VONSC05,NUMCOST)
       CALL PCTILE(CUM,VONSCOS,.50,VONSC50,NUMCOST)
       CALL PCTILE(CUM,VONSCOS,.95,VONSC95,NUMCOST)
       CUM(1)=PQ(1)/2.
       DO 22 I=2,NUMSAMP
         CUM(I)=CUM(I-1)+PQ(I)
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22      CONTINUE
C       FIND PERCENTILES OF CHANGE IN CORE MELT FREQUENCY
        CALL PCTILE(CUM,DFMD,.05,DFMD05,NUMSAMP)
        CALL PCTILE(CUM,DFMD,.50,DFMD50,NUMSAMP)
        CALL PCTILE(CUM,DFMD,.95,DFMD95,NUMSAMP)
C       EARLY FATALITIES
        DO 24 I=1,NUMSAMP
          VTEMP(I)=1.E6*DR(I,KFAT)*FACTP
          PQ(I)=PROB(I)
24      CONTINUE
        CALL SORT(VTEMP,PQ,NUMSAMP)
        CUM(1)=PQ(1)/2.
        DO 25 I=2,NUMSAMP
          CUM(I)=CUM(I-1)+PQ(I)
25      CONTINUE
        CALL PCTILE(CUM,VTEMP,.05,VEF05,NUMSAMP)
        CALL PCTILE(CUM,VTEMP,.50,VEF50,NUMSAMP)
        CALL PCTILE(CUM,VTEMP,.95,VEF95,NUMSAMP)
C       EARLY ILLNESS
        DO 241 I=1,NUMSAMP
          VTEMP(I)=1.E5*DR(I,KILL)*FACTP
          PQ(I)=PROB(I)
241     CONTINUE
        CALL SORT(VTEMP,PQ,NUMSAMP)
        CUM(1)=PQ(1)/2.
        DO 251 I=2,NUMSAMP
          CUM(I)=CUM(I-1)+PQ(I)
251     CONTINUE
        CALL PCTILE(CUM,VTEMP,.05,VEI05,NUMSAMP)
        CALL PCTILE(CUM,VTEMP,.50,VEI50,NUMSAMP)
        CALL PCTILE(CUM,VTEMP,.95,VEI95,NUMSAMP)
C       LATENT FATALITIES
        DO 242 I=1,NUMSAMP
          VTEMP(I)=1.E5*DR(I,KLAT)*FACTP
          PQ(I)=PROB(I)
242     CONTINUE
        CALL SORT(VTEMP,PQ,NUMSAMP)
        CUM(1)=PQ(1)/2.
        DO 252 I=2,NUMSAMP
          CUM(I)=CUM(I-1)+PQ(I)
252     CONTINUE
        CALL PCTILE(CUM,VTEMP,.05,VLF05,NUMSAMP)
        CALL PCTILE(CUM,VTEMP,.50,VLF50,NUMSAMP)
        CALL PCTILE(CUM,VTEMP,.95,VLF95,NUMSAMP)
C       PROPERTY DAMAGE
        DO 243 I=1,NUMSAMP
          VTEMP(I)=DR(I,KCOS)*FACTP
          PQ(I)=PROB(I)
243     CONTINUE
        CALL SORT(VTEMP,PQ,NUMSAMP)
        CUM(1)=PQ(1)/2.
        DO 253 I=2,NUMSAMP
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            CUM(I)=CUM(I-1)+PQ(I)
253    CONTINUE
       CALL PCTILE(CUM,VTEMP,.05,VPD05,NUMSAMP)
       CALL PCTILE(CUM,VTEMP,.50,VPD50,NUMSAMP)
       CALL PCTILE(CUM,VTEMP,.95,VPD95,NUMSAMP)
C      FIND TOTAL AVERTED OFFSITE COSTS
       DO 30 I=1,NUMSAMP
C      BASED ON COMPUTED COSTS
          VOFSC1(I)=(1.E6*DR(I,KFAT)+1.E5*(DR(I,KILL)+DR(I,KLAT))
      $          +DR(I,KCOS))*FACTP
C      BASED ON $1000/MAN-REM
          VOFSC2(I)=1.E3*DR(I,KDOS)*FACTP
          POFF(I)=PROB(I)
30     CONTINUE
C      SORT OFFSITE COSTS AND FIND PERCENTILES
       CALL SORT(VOFSC1,POFF,NUMSAMP)
       CALL SORT(VOFSC2,POFF,NUMSAMP)
       CUM(1)=POFF(1)/2.
       DO 50 I=2,NUMSAMP
          CUM(I)=CUM(I-1)+POFF(I)
50     CONTINUE
       CALL PCTILE(CUM,VOFSC1,.05,VOFSC105,NUMSAMP)
       CALL PCTILE(CUM,VOFSC1,.50,VOFSC150,NUMSAMP)
       CALL PCTILE(CUM,VOFSC1,.95,VOFSC195,NUMSAMP)
       CALL PCTILE(CUM,VOFSC2,.05,VOFSC205,NUMSAMP)
       CALL PCTILE(CUM,VOFSC2,.50,VOFSC250,NUMSAMP)
       CALL PCTILE(CUM,VOFSC2,.95,VOFSC295,NUMSAMP)
C      FIND TOTAL COSTS
       DO 40 JCOST=1,MAXCOSTIN
          DO 45 ISAMP=1,NUMSAMP
             KCOST=(JCOST-1)*NUMSAMP+ISAMP
             TOTCOS1(KCOST)=VONSCOS(KCOST)+VOFSC1(ISAMP)
             TOTCOS2(KCOST)=VONSCOS(KCOST)+VOFSC2(ISAMP)
             PTOT(KCOST)=PROB(ISAMP)/3.
45        CONTINUE
40     CONTINUE
C      SORT TOTAL COSTS AND FIND PERCENTILES
       CALL SORT(TOTCOS1,PTOT,NUMCOST)
       CALL SORT(TOTCOS2,PTOT,NUMCOST)
       CUM(1)=PTOT(1)/2.
       DO 55 ICOST=2,NUMCOST
          CUM(ICOST)=CUM(ICOST-1)+PTOT(ICOST)
55     CONTINUE
       CALL PCTILE(CUM,TOTCOS1,.05,TOTCOS105,NUMCOST)
       CALL PCTILE(CUM,TOTCOS1,.50,TOTCOS150,NUMCOST)
       CALL PCTILE(CUM,TOTCOS1,.95,TOTCOS195,NUMCOST)
       CALL PCTILE(CUM,TOTCOS2,.05,TOTCOS205,NUMCOST)
       CALL PCTILE(CUM,TOTCOS2,.50,TOTCOS250,NUMCOST)
       CALL PCTILE(CUM,TOTCOS2,.95,TOTCOS295,NUMCOST)
C      FIND COSTS OF IMPLEMENTATION OF SAFETY OPTION
       DO 140 J=1,MAXCOSTIN
          XI2(J)=COPER(J)*FACTP
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      XI3(J)=PMWE*CAPF*PPCI(J)*TRPINST(J)/65.
      IF(DISCR.NE.ESCR)THEN
        XI4(J)=PMWE*CAPF*PPCI(J)*TRPOPER(J)*(1.-EXP(-(DISCR-ESCR)
     $           *JREM))/(DISCR-ESCR)/65.
      ELSE
        XI4(J)=PMWE*CAPF*PPCI(J)*TRPOPER(J)*JREM/65.
      ENDIF
      TOTIMP(J)=CINST(J)+XI2(J)+XI3(J)+XI4(J)
140   CONTINUE
      WRITE(1,1130)NAMALT
      WRITE(3,1130)NAMALT
1130  FORMAT('1       SAFETY OPTION :',A/
     $        5X,'VALUE-IMPACT ANALYSIS '/
     $        43X,'LOW',9X,'CENTRAL',5X,'HIGH')
      WRITE(1,1140)DFMD05,DFMD50,DFMD95
      WRITE(3,1140)DFMD05,DFMD50,DFMD95
1140  FORMAT(5X,'CHANGE IN CORE MELT FREQUENCY',6X,1P3E12.3//
     $        ' COSTS:')
      WRITE(1,1150)(CINST(J),J=1,MAXCOSTIN)
      WRITE(3,1150)(CINST(J),J=1,MAXCOSTIN)
1150  FORMAT(5X,'INSTALLATION & ENG. COSTS',10X,1P3E12.3)
      WRITE(1,1160)(XI2(J),J=1,MAXCOSTIN)
      WRITE(3,1160)(XI2(J),J=1,MAXCOSTIN)
1160  FORMAT(5X,'OPERATING & MAINT. COSTS',11X,1P3E12.3)
      WRITE(1,1170)(XI3(J),J=1,MAXCOSTIN)
      WRITE(3,1170)(XI3(J),J=1,MAXCOSTIN)
1170  FORMAT(5X,'REPLACEMENT POWER DURING INST.',5X,1P3E12.3)
      WRITE(1,1180)(XI4(J),J=1,MAXCOSTIN)
      WRITE(3,1180)(XI4(J),J=1,MAXCOSTIN)
1180  FORMAT(5X,'REPLACEMENT POWER IN OPERATION',5X,1P3E12.3/
     $        40X,'----------------------------------')
      WRITE(1,1190)(TOTIMP(J),J=1,MAXCOSTIN)
      WRITE(3,1190)(TOTIMP(J),J=1,MAXCOSTIN)
1190  FORMAT(5X,'TOTAL COSTS',24X,1P3E12.3//' BENEFITS')
      WRITE(1,1200)VONSC05,VONSC50,VONSC95
      WRITE(3,1200)VONSC05,VONSC50,VONSC95
1200  FORMAT(5X,'AVERTED ON-SITE COST',15X,1P3E12.3)
      WRITE(1,1210)
      WRITE(3,1210)
1210  FORMAT(3X,'AVERTED OFFSITE COSTS')
      WRITE(1,1220)VPD05,VPD50,VPD95
      WRITE(3,1220)VPD05,VPD50,VPD95
1220  FORMAT(5X,'AVERTED PROPERTY DAMAGE',12X,1P3E12.3)
      WRITE(1,1230)VEF05,VEF50,VEF95
      WRITE(3,1230)VEF05,VEF50,VEF95
1230  FORMAT(5X,'VALUE OF AVERTED PROMPT FATALITY',3X,1P3E12.3)
      WRITE(1,1240)VEI05,VEI50,VEI95
      WRITE(3,1240)VEI05,VEI50,VEI95
1240  FORMAT(5X,'VALUE OF AVERTED EARLY ILLNESS',5X,1P3E12.3)
      WRITE(1,1250)VLF05,VLF50,VLF95
      WRITE(3,1250)VLF05,VLF50,VLF95
1250  FORMAT(5X,'VALUE OF AVERTED LAT. CANCER',7X,1P3E12.3/40X,
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     $         '-------------------------------------')
       WRITE(1,1260)VOFSC105,VOFSC150,VOFSC195
       WRITE(3,1260)VOFSC105,VOFSC150,VOFSC195
1260   FORMAT(5X,'TOTAL AVERTED OFFSITE COSTS',8X,1P3E12.3)
       WRITE(1,1270)VOFSC205,VOFSC250,VOFSC295
       WRITE(3,1270)VOFSC205,VOFSC250,VOFSC295
1270   FORMAT(5X,'OFFSITE COSTS AT $1000/P-REM',7X,1P3E12.3)
       WRITE(1,1280)TOTCOS105,TOTCOS150,TOTCOS195
       WRITE(3,1280)TOTCOS105,TOTCOS150,TOTCOS195
1280   FORMAT(5X,'TOTAL AVERTED ON & OFFSITE COSTS'/
     $         5X,'(BASED ON COMPUTED COSTS)',10X,1P3E12.3)
       WRITE(1,1290)TOTCOS205,TOTCOS250,TOTCOS295
       WRITE(3,1290)TOTCOS205,TOTCOS250,TOTCOS295
1290   FORMAT(5X,'(BASED ON $1000/P-REM)',13X,1P3E12.3)
       RETURN
       END
       SUBROUTINE RETEMAC(TEMFIL,SEQ_WORDS)
       INCLUDE 'GENPARAM2.FOR'
       INCLUDE 'EXPLAN2.FOR'
       INCLUDE 'GENCOM2.FOR'
       CHARACTER*50 TEMFIL
       CHARACTER*80 SEQ_WORDS
       OPEN(UNIT=5,FILE=TEMFIL,STATUS='OLD')
       READ(5,1000)SEQ_WORDS
1000   FORMAT(A80)
       DO 10 ISAMP=1,NUMSAMP
         READ(5,*)IOBS,LVEC,(FS(ISAMP,ISEQ),ISEQ=1,LVEC)
         IF(LVEC.LT.NUMSEQ)THEN
           TYPE*,'LVEC.LT.NUMSEQ'
           STOP
         ENDIF
10     CONTINUE
       CLOSE(UNIT=5)
       RETURN
       END
       SUBROUTINE RECODES(CODEFIL,CODE,CFM_WORDS,LCODE)
       INCLUDE 'GENPARAM2.FOR'
       INCLUDE 'EXPLAN2.FOR'
       INCLUDE 'GENCOM2.FOR'
       CHARACTER*50 CODE(MAXCFM),CODEFIL,CODEX
       CHARACTER*80 CFM_WORDS
       OPEN(UNIT=5,FILE=CODEFIL,STATUS='OLD')
       READ(5,1000)CFM_WORDS
1000   FORMAT(1X,A)
       READ(5,*)LCODE,NUMBINS
         IF(NUMBINS.NE.NUMCFM)THEN
           TYPE*,'NUMBINS .NE. NUMCFM'
           STOP
         ENDIF
       DO 10 IB=1,NUMBINS
         READ(5,1000)CODEX(1:LCODE)
         CODE(IB)=CODEX
```

B.72

```fortran
10      CONTINUE
        CLOSE(UNIT=5)
        RETURN
        END
        SUBROUTINE REDEVNT(PBINFIL,CODE,ICFG,SIZE)
        INCLUDE 'GENPARAM2.FOR'
        INCLUDE 'EXPLAN2.FOR'
        INCLUDE 'GENCOM2.FOR'
        INTEGER SIZE
        CHARACTER*50 CODE(MAXCFM),CODEX,PBINFIL
        CHARACTER*80 TRASH
          DIMENSION PBIN(MAXCFM)
C
C          OPEN FILE AND STRIP HEADER
        OPEN(UNIT=5,FILE=PBINFIL,STATUS='OLD')
        READ(5,1000)TRASH
1000    FORMAT(A)
        NAMCFG(ICFG)=TRASH(1:6)
C
C          LOOP OVER OBSERVATIONS
        DO 250 ISAMP=1,NUMSAMP
C
C          GET NUMBER OF BINS FOR OBSERVATION
        READ(5,*)IK,NBINS(ICFG,ISAMP)
        IF(IK.NE.ISAMP)THEN
          TYPE*,'IOBS=',IK,' ISAMP=',ISAMP,'SEQ=',NAMCFG(ICFG)
          STOP
        ENDIF
        IF(NBINS(ICFG,ISAMP).GT.NUMCFM)THEN
          TYPE*,'NBINS>NUMBINS, ICFG=',ICFG
          STOP
        ENDIF
C
C          SET UP STORAGE STARTING LOCATION
        IF(NEXTFRE.GT.0) THEN
          ISTRT=NEXTFRE
          LASTPBN=NEXTFRE-1
          NEXTFRE=0
        ELSE
          ISTRT=LASTPBN+1
        ENDIF
        SUM=0.0
        ISTRTG(ICFG,ISAMP)=ISTRT
C
C          LOOP OVER BINS
        DO 25 IBIN=1,NBINS(ICFG,ISAMP)
C
C             READ BIN AND PROBABILITY
          READ(5,1010)CODEX(1:SIZE),PBIN(IBIN)
1010      FORMAT(A,E11.3)
C
C             FIND POSITION IN BIN LIST
```

```fortran
                DO 30 ICFM=1,NUMCFM
                IF(CODEX.NE.CODE(ICFM))GOTO 30
                  IPOINT(ISTRT+IBIN-1)=ICFM
                  SUM=SUM+PBIN(IBIN)
                  GOTO 25
30              CONTINUE
C
C                 BIN NOT IN BIN LIST
                  TYPE*,'ISAMP=',ISAMP,' ICFG=',ICFG,' IBIN=',IBIN
                  IF(IOPT(13))  STOP
25            CONTINUE
C
C             CHECK FOR SUM TO ONE
            IF(ABS(1.-SUM).GT.0.01)THEN
C               TYPE*,'ISAMP=',ISAMP,' ICFG=',ICFG,' SUM=',SUM
                IF(IOPT(12)) STOP
            ENDIF
C
C             NORMALIZE IF REQUESTED
              IF(IOPT(11)) THEN
              DO 252 IBIN=1,NBINS(ICFG,ISAMP)
                PBIN(IBIN)=PBIN(IBIN)/SUM
252           CONTINUE
              ENDIF
C
C             FILLIN STORAGE ARRAY
              DO 251 IBIN=1,NBINS(ICFG,ISAMP)
                  PRBLST(IBIN+ISTRT-1)= PBIN(IBIN)
251           CONTINUE
C
C             SET LAST USED LOCATION
              LASTPBN=LASTPBN+NBINS(ICFG,ISAMP)
              IF(LASTPBN.GT.MAXCFG*MAXSAMP*MAVPCFG*2) THEN
                TYPE*,'LASTPBN=',LASTPBN,
     *               ' MAXIMUM=MAXCFG*MAXSAMP*MAVPCFG*2=',
     *               MAXCFG*MAXSAMP*MAVPCFG*2
                STOP
              ENDIF
250       CONTINUE
          CLOSE(UNIT=5)
        RETURN
        END
          FUNCTION PFGM(ISAMP,ICFG,ICFM)
        INCLUDE 'GENPARAM2.FOR'
        INCLUDE 'EXPLAN2.FOR'
        INCLUDE 'GENCOM2.FOR'
          IF(ISAMP.NE.ISLAST) THEN
C           GET DATA FROM STORAGE ARRAY
C
C           INITIALIZE TO 0.0
            DO 200 IG=1,NUMCFG
              DO 100 IM=1,NUMCFM
```

```
                  PROBIN(IM,IG)=0.0
  100         CONTINUE
  200      CONTINUE
C
C         SUBSTITUTE ACCORDING TO POINTERS
          DO 400 IG=1,NUMCFG
            III=ISTRTG(IG,ISAMP)-1
            DO 300 IM=1,NBINS(IG,ISAMP)
              PROBIN(IPOINT(III+IM),IG)=PRBLST(III+IM)
  300       CONTINUE
  400      CONTINUE
          ISLAST=ISAMP
         ENDIF
C
C        ASSIGN VALUE
         PFGM=PROBIN(ICFM,ICFG)
         RETURN
         END
       SUBROUTINE REDPOINT(POINTFIL,REL_WORDS)
       INCLUDE'GENPARAM2.FOR'
       INCLUDE 'EXPLAN2.FOR'
       INCLUDE 'GENCOM2.FOR'
       CHARACTER*50 POINTFIL
       CHARACTER*80 REL_WORDS
       OPEN (UNIT=5,FILE=POINTFIL,STATUS='OLD')
       READ(5,1000)REL_WORDS
 1000  FORMAT(A80)
       READ(5,*)NCLUST
       NUMREL=NCLUST
         READ(5,*)((IRSM(ISAMP,ICFM),ICFM=1,NUMCFM),
      $            ISAMP=1,NUMSAMP)
       CLOSE(UNIT=5)
       RETURN
       END
       SUBROUTINE REDCONS(CONSFIL,ICSQVECT)
       INCLUDE 'GENPARAM2.FOR'
       INCLUDE 'EXPLAN2.FOR'
       INCLUDE 'GENCOM2.FOR'
       CHARACTER*50 CONSFIL
       OPEN(UNIT=5,FILE=CONSFIL,STATUS='OLD')
       DO 10 IREL=1,NUMREL
         READ(5,1000)NAMREL(IREL)
 1000    FORMAT(A)
         DO 15 ICSQ=1,NUMCSQ
          READ(5,*)CR(IREL,ICSQ)
  15     CONTINUE
  10   CONTINUE
       CLOSE(UNIT=5)
       RETURN
       END
       SUBROUTINE FCHISQ(ICSQ)
C      FOR EACH ISSUE, COMPUTES NO. BELOW AND ABOVE MEDIAN, AND
```

```
C        COMPARES WITH NO. EXPECTED IF DISTRIBUTION WERE FLAT.
C        THE CHI-SQUARED TEST FOR DEVIATION FROM A FLAT DISTRIBUTION
C        IS PERFORMED FOR EACH LEVEL AND FOR THE ISSUE AS A WHOLE.
C        A SIGNIFICANCE < 0.1 INDICATES REASONABLE PROBABILITY
C        THAT THE DEVIATION IS NOT DUE TO CHANCE ALONE.
         INCLUDE 'GENPARAM2.FOR'
         INCLUDE 'EXPLAN2.FOR'
         INCLUDE 'GENCOM2.FOR'
         DIMENSION RX(MAXSAMP),IX(MAXSAMP),XX(MAXSAMP)
         WRITE(1,999)NAMCSQ(ICSQ)
999      FORMAT('1      CONSEQUENCE MEASURE:   ',A)
C        ORDER RISK
         DO 10 ISAMP=1,NUMSAMP
           RX(ISAMP)=R(ISAMP,ICSQ)
           XX(ISAMP)=ISAMP
10       CONTINUE
         CALL SORT(RX,XX,NUMSAMP)
         DO 15 ISAMP=1,NUMSAMP
           IX(ISAMP)=XX(ISAMP)
15       CONTINUE
C        FIND MEDIAN RISK
         IMED=NUMSAMP/2
         RMED=RX(IMED)
C        STEP THROUGH ISSUES
         DO 20 ISSGP=1,NUMISSGP
           DO 25 ISS=1,NUMISS(ISSGP)
C        FOR EACH LEVEL OF THIS ISSUE, FIND NO. OF EXEMPLARS, AND
C        NUMBER BELOW MEDIAN.
              NUMLEV=NUMLVL(ISS,ISSGP)
              IF(NUMLEV.EQ.1)GOTO 25
              WRITE(1,1000)ISSGP,ISS,NAMISS(ISS,ISSGP)
1000     FORMAT('0     ISSUE GROUP = ',I3,'    ISSUE = ',I3,3X,A)
              NDOF=2*NUMLEV-1
              BIGCHI=0.
              DO 30 LEV=1,NUMLEV
                NZAHL=0
                NLOW=0
                DO 35 ISAMP=1,NUMSAMP
                  IK=IX(ISAMP)
                  IF(LVL(ISSGP,ISS,IK).NE.LEV)GOTO 35
                  NZAHL=NZAHL+1
                  IF(RX(ISAMP).GE.RMED)GOTO 35
                  NLOW=NLOW+1
35              CONTINUE
                NHIGH=NZAHL-NLOW
                NEXPL=NZAHL/2
                NEXPH=NZAHL-NEXPL
                IF(NEXPL.GE.5.AND.NEXPH.GE.5)THEN
                  X1LO=NLOW
                  X2LO=NEXPL
                  X1HI=NHIGH
                  X2HI=NEXPH
```

```
                  CHISQ=(X1LO-X2LO)**2/X2LO+(X1HI-X2HI)**2/X2HI
                  BIGCHI=BIGCHI+CHISQ
                  NU=1
                  CALL QCHISQ(CHISQ,NU,Q)
                  WRITE(1,1200)LEV,NLOW,NEXPL,NHIGH,NEXPH,CHISQ,NU,Q
1200     FORMAT(/5X,'LEVEL',I2,' NO.<MED.=',I3,' NO. EXP.=',I3,
         $           '      NO.>=MED.=',I3,' NO. EXP.=',I3,'    CHI-SQ.=',
         $           F6.1,' DF=',I2,' SIG.=',F6.3)
              ELSE IF(NEXPL.LT.3.OR.NEXPH.LT.3)THEN
                  WRITE(1,1205)LEV,NLOW,NEXPL,NHIGH,NEXPH
1205     FORMAT(/5X,'LEVEL',I2,' NO.<MED.=',I3,' NO. EXP.=',I3,
         $           '      NO.>=MED.=',I3,' NO. EXP.=',I3,
         $           '   CHI-SQ. TEST CANNOT BE RUN; EXP. NO. < 3')
                  NDOF=NDOF-2
              ELSE
C        PIRIE-HAMDEN CORRECTION
                  A=X1LO
                  B=X2LO
                  C=X1HI
                  D=X2HI
                  SI=X1LO+X2LO
                  SJ=X1HI+X2HI
                  SK=X1LO+X1HI
                  SL=X2LO+X2HI
                  CHISQ=NZAHL*(ABS(A*D-B*C)-.5)**2/(SI*SJ*SK*SL)
                  BIGCHI=BIGCHI+CHISQ
                  NU=1
                  CALL QCHISQ(CHISQ,NU,Q)
                  WRITE(1,1200)LEV,NLOW,NEXPL,NHIGH,NEXPH,CHISQ,NU,Q
              ENDIF
30            CONTINUE
                  IF(NDOF.LT.1)GOTO 25
              CALL QCHISQ(BIGCHI,NDOF,Q)
              WRITE(1,1220)BIGCHI,NDOF,Q
1220     FORMAT(/5X,'OVERALL CHI-SQ=',F6.1,' DF=',I3,'   SIG.=',F6.3//)
25            CONTINUE
20       CONTINUE
         RETURN
         END
         SUBROUTINE QCHISQ(CHISQ,NU,Q)
C        A SUBROUTINE TO CALCULATE PERCENTAGE POINTS OF THE CHI-SQUARED
C        DISTRIBUTION.  NU = DEGREES-OF-FREEDOM.
         SUM=0.
         PROD=1.
         CHI=SQRT(CHISQ)
         ZCHI=EXP(-CHISQ/2.)*.398942
C        FIND IF NU IS ODD OR EVEN
         XX=NU/2.
         IF(XX.EQ.NU/2)GOTO 100
C        NU IS ODD; ABRAMOWITZ AND STEGUN, 26.4.4
         T=1./(1.+.33267*CHI)
         QCHI=ZCHI*(.4361836*T-.1201676*T**2+.937298*T**3)
```

```
         LIM=(NU-1)/2
         IF(LIM.EQ.0)GOTO 20
         DO 10 L=1,LIM
            PROD=PROD*(2*L-1)
            SUM=SUM+CHI**(2*L-1)/PROD
10       CONTINUE
20       Q=2.*QCHI+2.*ZCHI*SUM
         RETURN
C        NU IS EVEN; A & S, 26.4.5
100      LIM=(NU-2)/2
         IF(LIM.EQ.0.)GOTO 120
         DO 110 L=1,LIM
            PROD=PROD*2.*L
            SUM=SUM+CHI**(2.*L)/PROD
110      CONTINUE
120      Q=2.506628*ZCHI*(1.+SUM)
         RETURN
         END
         SUBROUTINE DETANAL
         INCLUDE 'GENPARAM2.FOR'
         INCLUDE 'EXPLAN2.FOR'
         INCLUDE 'GENCOM2.FOR'
C        PROVIDES A DETAILED ANALYSIS OF EACH OF UP TO 20 SAMPLE
C        MEMBERS.  FOR EACH SAMPLE MEMBER THE RISK AND THE
C        CONTRIBUTIONS TO RISK FOR EACH SEQUENCE AND CFM WILL
C        BE PRINTED OUT.
         DIMENSION CONTR(MAXSEQ,MAXCFM),RX(MAXSAMP),XX(MAXSAMP),
     $              . FRSEQ(MAXSEQ),FRCFM(MAXCFM),FRREL(MAXREL)
         CHARACTER*50 CODE,CODEX
            CHARACTER*130 F1099
         COMMON/CODECOM/CODE(MAXCFM),LCODE
C        CONTR(ISEQ,IGFM)=CONTRIBUTION TO RISK FOR ICFM, IN SEQUENCE
C        ISEQ.
C
C        FIRST; STEP THROUGH CONSEQUENCES.
         DO 10 ICSQ=1,NUMCSQ
C        NOW SORT RISK
            DO 15 ISAMP=1,NUMSAMP
               RX(ISAMP)=R(ISAMP,ICSQ)
               XX(ISAMP)=ISAMP
15          CONTINUE
            CALL SORT(RX,XX,NUMSAMP)
C        NOW PICK OUT THE SELECTED SAMPLE MEMBERS
            DO 20 JSEL=1,NUMSEL
               DO 12 ISEQ=1,NUMSEQ
12             FRSEQ(ISEQ)=0.     .
               DO 14 ICFM=1,NUMCFM
14             FRCFM(ICFM)=0.
               DO 16 IREL=1,NUMREL
16             FRREL(IREL)=0.
               INUM=ISEL(JSEL)
               IS=XX(INUM)
```

```
            IF(RX(INUM).LE.0.0) GOTO 20
            WRITE(1,1000)NAMCSQ(ICSQ)
1000        FORMAT(1H1,4X,'CONSEQUENCE MEASURE:   ',A/
     $             5X,'DETAILED ANALYSIS OF INDIVIDUAL SAMPLE MEMBERS')
            WRITE(1,1010)JSEL,INUM,IS,RX(INUM)
1010        FORMAT(//5X,'SELECTION NO. ',I3,5X,I3,'-TH FROM BOTTOM',
     $             5X,'SAMPLE MEMBER ',I3,'  RISK=',1PE10.3)
            F1099(1:38)='(/'       SEQ.           FREQ.       CFM'','
            IF(LCODE.LT.10) THEN
               WRITE(F1099(39:43),1111) LCODE
            ELSE
               WRITE(F1099(39:43),1112) LCODE
            END IF
1111        FORMAT(I1,'X,')
1112        FORMAT(I2,'X,')
            F1099(44:130)=''' PROB.        REL  CONS.  CONTRIB.'')'
            WRITE(1,F1099)
          DO 30 ISEQ=1,NUMSEQ
            NCFG=ICFGS(ISEQ)
            DO 32 ICFM=1,NUMCFM
            JRSM=IRSM(IS,ICFM)
               IF(JRSM.LE.0) THEN
                  CONTR(ISEQ,ICFM)=0.0
               ELSE
               CONTR(ISEQ,ICFM)=PFGM(IS,NCFG,ICFM)*FS(IS,ISEQ)
     $                    *CR(JRSM,ICSQ)
               FRSEQ(ISEQ)=FRSEQ(ISEQ)+CONTR(ISEQ,ICFM)/RX(INUM)
               FRCFM(ICFM)=FRCFM(ICFM)+CONTR(ISEQ,ICFM)/RX(INUM)
               FRREL(JRSM)=FRREL(JRSM)+CONTR(ISEQ,ICFM)/RX(INUM)
               ENDIF
32          CONTINUE
30          CONTINUE
          DO 40 ISEQ=1,NUMSEQ
            SUMSEQ=0.
            DO 44 ICFM=1,NUMCFM
            SUMSEQ=SUMSEQ+CONTR(ISEQ,ICFM)
44          CONTINUE
C     IF CONTRIBUTION IS < 1%, IGNORE
            IF(SUMSEQ.LT..01*RX(INUM))GOTO 40
            WRITE(1,1100)NAMSEQ(ISEQ),FS(IS,ISEQ),SUMSEQ
1100        FORMAT(/5X,A10,1PE10.2,52X,E10.2)
            DO 46 ICFM=1,NUMCFM
            IF(CONTR(ISEQ,ICFM).LT..01*SUMSEQ)GOTO 46
            NCFG=ICFGS(ISEQ)
            JRSM=IRSM(IS,ICFM)
            CODEX=CODE(ICFM)
            WRITE(1,1110)CODEX(1:LCODE),PFGM(IS,NCFG,ICFM),
     $             JRSM,CR(JRSM,ICSQ),CONTR(ISEQ,ICFM)
1110        FORMAT(30X,A,F10.4,I5,1P2E10.2)
46          CONTINUE
40          CONTINUE
          WRITE(1,2000)NAMCSQ(ICSQ)
```

```
2000      FORMAT(1H0,4X,A)
          WRITE(1,1200)
1200      FORMAT(5X,'FRACTIONAL CONTRIBUTIONS OF EACH SEQUENCE')
          DO 50 ISEQ=1,NUMSEQ
C             IF(FRSEQ(ISEQ).LT..01)GOTO 50
            WRITE(1,1210)NAMSEQ(ISEQ),FRSEQ(ISEQ)
1210        FORMAT(5X,A10,F10.4)
50        CONTINUE
          WRITE(1,2000)NAMCSQ(ICSQ)
          WRITE(1,1300)
1300      FORMAT(5X,'FRACTIONAL CONTRIBUTIONS OF EACH CF BIN')
          DO 60 ICFM=1,NUMCFM
            IF(FRCFM(ICFM).LT..01)GOTO 60
            CODEX=CODE(ICFM)
            WRITE(1,1211)CODEX(1:LCODE),FRCFM(ICFM)
1211        FORMAT(5X,A,F10.4)
60        CONTINUE
          WRITE(1,2000)NAMCSQ(ICSQ)
          WRITE(1,1400)
1400      FORMAT(5X,'FRACTIONAL CONTRIBUTIONS OF EACH RELEASE')
          DO 70 IREL=1,NUMREL
            IF(FRREL(IREL).LT..01)GOTO 70
            WRITE(1,1210)NAMREL(IREL),FRREL(IREL)
70        CONTINUE
20        CONTINUE
10      CONTINUE
        RETURN
        END
        SUBROUTINE CCDF
        INCLUDE 'GENPARAM2.FOR'
        INCLUDE 'EXPLAN2.FOR'
        INCLUDE 'GENCOM2.FOR'
        PARAMETER (MAXDPT=50)
        DIMENSION XDPT(MAXDPT),PREL(MAXREL,MAXSAMP),YDPT(MAXDPT,MAXSAMP),
     $            X1DPT(MAXDPT,MAXREL,MAXCSQ),Y1DPT(MAXDPT,MAXREL,MAXCSQ),
     $            XX(MAXSAMP),YY(MAXSAMP),Y2DPT(MAXDPT,MAXREL),
     $            X0DPT(MAXDPT),CUM(MAXSAMP),ICCDF(MAXCSQ)
        CHARACTER*80 JUNK
        LOGICAL ICCDF
        DATA(XDPT(I),I=1,5)/.01,.02,.03,.05,.07/
        NUMDPT=50
        DO 1 I=6,NUMDPT
          XDPT(I)=10.*XDPT(I-5)
1       CONTINUE
C       FIND RELEASE FREQUENCIES
        DO 10 ISAMP=1,NUMSAMP
          DO 15 IREL=1,NUMREL
            PREL(IREL,ISAMP)=0.
15        CONTINUE
          DO 20 ISEQ=1,NUMSEQ
            JCFG=ICFGS(ISEQ)
            DO 25 ICFM=1,NUMCFM
```

```
                  JREL=IRSM(ISAMP,ICFM)
                  PREL(JREL,ISAMP)=PREL(JREL,ISAMP)+FS(ISAMP,ISEQ)*
      $              PFGM(ISAMP,JCFG,ICFM)
25            CONTINUE
20         CONTINUE
10      CONTINUE
C     STEP THROUGH RELEASES AND CONSEQUENCE MEASURES
        OPEN(UNIT=10,FILE='CCDF.DAT',STATUS='OLD')
        OPEN(UNIT=12,FILE='CCDF.PLT',STATUS='NEW')
        READ(10,999)(ICCDF(IC),IC=1,NUMCSQ)
999     FORMAT(10L1)
        DO 300 IREL=1,NUMREL
          DO 310 ICSQ=1,NUMCSQ
            IF(.NOT.ICCDF(ICSQ))GOTO 310
            READ(10,800)JUNK
800         FORMAT(A)
            READ(10,*)NDPT
            DO 312 II=1,NDPT
              READ(10,*)KDPT,X1DPT(II,IREL,ICSQ),Y1DPT(II,IREL,ICSQ)
312         CONTINUE
            IF(NDPT.LT.NUMDPT)THEN
              NP1=NDPT+1
              DO 311 II=NP1,NUMDPT
              X1DPT(II,IREL,ICSQ)=10.*X1DPT(II-5,IREL,ICSQ)
              Y1DPT(II,IREL,ICSQ)=0.0
311           CONTINUE
            ENDIF
310       CONTINUE
300     CONTINUE
        DO 30 ICSQ=1,NUMCSQ
          IF(.NOT.ICCDF(ICSQ))GOTO 30
          WRITE(12,1800)NAMCSQ(ICSQ)
1800      FORMAT(5X,A80)
          DO 330 IDPT=1,NUMDPT
            X0DPT(IDPT)=XDPT(IDPT)
330       CONTINUE
          DO 28 IREL=1,NUMREL
            DO 40 I=1,NUMDPT
              X3=X0DPT(I)
              DO 45 J=2,NUMDPT
                IF(X1DPT(J,IREL,ICSQ).LT.X0DPT(I))GOTO 45
                GOTO 50
45            CONTINUE
              J=NUMDPT
50            X1=X1DPT(J-1,IREL,ICSQ)
              X2=X1DPT(J,IREL,ICSQ)
              Y1=Y1DPT(J-1,IREL,ICSQ)
              Y2=Y1DPT(J,IREL,ICSQ)
              Y3=Y1+(X3-X1)*(Y2-Y1)/(X2-X1)
              Y2DPT(I,IREL)=MIN(Y3,1.0)
40          CONTINUE
28        CONTINUE
```

```
C     SET UP CCDF FOR EACH SAMPLE MEMBER
         DO 60 IDPT=1,NUMDPT
           DO 65 ISAMP=1,NUMSAMP
               YDPT(IDPT,ISAMP)=0.0
             . DO 70 IREL=1,NUMREL
                 YDPT(IDPT,ISAMP)=YDPT(IDPT,ISAMP)+PREL(IREL,ISAMP)*
     $                 Y2DPT(IDPT,IREL)
70             CONTINUE
               YDPT(IDPT,ISAMP)=MAX(YDPT(IDPT,ISAMP),0.)
               YDPT(IDPT,ISAMP)=MIN(YDPT(IDPT,ISAMP),FMD(ISAMP))
               XX(ISAMP)=YDPT(IDPT,ISAMP)
               YY(ISAMP)=ISAMP
65           CONTINUE
             CALL SORT(XX,YY,NUMSAMP)
             IF(XX(NUMSAMP).EQ.0.)GOTO 33
             CUM(1)=1./NUMSAMP/2.
             DO 75 I=2,NUMSAMP
               XJ=I
               CUM(I)=(2.*XJ-1.)/NUMSAMP/2.
75           CONTINUE
             CALL PCTILE(CUM,XX,.05,Y05,NUMSAMP)
             CALL PCTILE(CUM,XX,.95,Y95,NUMSAMP)
             WRITE(12,2000)XODPT(IDPT),Y05,Y95,(XX(ISAMP),ISAMP=
     $                 1,NUMSAMP)·
2000  FORMAT(1PE12.3/2E12.3/(10E12.3))
60        CONTINUE
33    XEND=-999.
      WRITE(12,2005)XEND
2005  FORMAT(1PE12.3)
30    CONTINUE
      CLOSE(UNIT=10)
      CLOSE(UNIT=12)
      RETURN
      END
```

APPENDIX C

ANALYSIS OF ACCIDENT PROGRESSION AND CONTAINMENT RESPONSE

C.0   ANALYSIS OF ACCIDENT PROGRESSION AND CONTAINMENT RESPONSE

After the frequency of core damage is calculated, the next task is the modeling of the accident progression both in the reactor vessel and after the core debris leaves the vessel. The response of the containment to the accident progression is of particular interest since the containment is the last barrier between the radioactive material in the core and the environment. An overview of the methods used in the accident progression and containment response analysis is presented in Chapter 6. This Appendix presents further detail on some aspects of this analysis that could not be discussed in Chapter 6.

Section C.1 is an introduction to this appendix. The features of EVNTRE, the code which processes the accident progression event trees, are summarized in Section C.2. This material is placed before the discussion of the event trees themselves because a knowledge of the capabilities of the processing code makes understanding the nature and scope of the event trees easier. Section C.3 describes the steps in the development of the event trees used in the accident progression and containment response analysis. The major time periods considered in the event trees are discussed in this section. Section C.4 concerns the quantification of the event tree, that is, the process of obtaining distributions or fixed numerical values for each branch probability and each parameter in the event tree. The final section, C.5, discusses evaluation of the tree and rebinning of the results.

C.1   Introduction

The objectives of the accident progression and containment response analysis and the methods adopted for the analysis have been described in Sections 6.1 and 6.2. The PRAs performed in support of NUREG-1150,[1] including quantitative representation of uncertainty, required a more flexible and efficient approach than that provided by placing all accident results in a few bins for which the results of mechanistic code calculations were available. As used in the PRAs performed for NUREG-1150, the event trees used for the accident progression and containment response analysis served as logical and probabilistic frameworks for synthesizing the results of the mechanistic models. These event trees are referred to as APETs, which stand for Accident Progression Event Trees.

The rapid and efficient evaluation of event trees in a manner compatible with the Monte Carlo approach to the consideration of uncertainties required the development of a new computer code, EVNTRE,[2] to evaluate event trees. This code is not specific to accident progression analysis, but is a general, powerful and flexible manipulator of event tree logic. The use of event trees for the accident progression and containment response analysis does not eliminate the use of the mechanistic codes. Indeed, the results of these codes are used to establish the basic structure of the tree, to determine what events should be included, and they provide the basis for the quantification of the tree.

C.2   Capabilities of the EVNTRE Code

The accident progression and containment response analysis is performed using large, complex event trees which are evaluated by EVNTRE. Because the nature of the event trees depends on the capabilities of the evaluation code, this summary

of EVNTRE is placed before the discussion of event tree development. The material in this section is drawn from the EVNTRE reference manual and provides only a summary of the features of EVNTRE.

Subsection C.2.1 discusses the general features of EVNTRE. Subsection C.2.2 presents the different types of questions recognized by EVNTRE, and Subsection C.2.3 explains the case structure used to allow the branch probabilities to depend on the path taken through the tree. Subsection C.2.4 discusses the input and output files for EVNTRE and how EVNTRE is used in the sampling mode.

C.2.1   General Features of EVNTRE

The general capabilities of the EVNTRE program used to evaluate the event trees utilized for the accident progression and containment response analysis are described in this section. While several automated event tree quantification schemes have been developed in the past, EVNTRE represents a significant advance in capabilities for event tree evaluation. Specific features include:

- More than two branches are permitted per question, i.e., there is not a limitation of only two outcomes at each question;

- Branch probabilities dependent on the path through the tree by means of case structure for each question;

- Representation of continuous variables, such as pressures and temperatures, by FORTRAN real variables known as parameters;

- Ability to select a branch at a question based on parameter values or simple combinations of parameter values;

- Ability to evaluate user supplied FORTRAN subprograms during the evaluation of the APET in order to manipulate the parameters; and

- Flexible classification of the results (binning) to sort the myriad paths through the tree into a manageable set of bins.

This last feature is of particular importance. These large event trees have far too many paths through them for each path to be examined individually by the analyst. Therefore, an input file separate from the file which contains the event tree itself is required to provide instructions to EVNTRE as to how to group the paths into bins. These bins form the interface between the accident progression analysis and the source term analysis as explained in Section 6.4. This input file of grouping and sorting instructions is known as the binner.

EVNTRE can evaluate event trees with more than 100 questions, most of which have more than two branches. This allows more effective modeling of accident progression by separation of the accident progression into multiple time regimes. For example, hydrogen generation and combustion can be treated in several time periods during the progression of the core melt process. By passing parameter values from one time period to the next, consistency is assured.

C.2

Due to the complexity and length of the event trees utilized for the accident progression and containment response analyses for NUREG-1150, the EVNTRE code was developed with provisions to assist in the development of the trees and the diagnosis of errors. The input file that constitutes the event tree must be in the proper form and consistent. For example, error messages are generated if the branch probabilities do not sum to 1.0 exactly or when the input for a case indicates that there are three conditions but only two are supplied. EVNTRE cannot, however, catch errors in which the event tree is in the proper form but the logic expressed in the tree is not appropriate for the plant being analyzed and the physical processes taking place. These errors can be prevented only by careful development of the tree by the analyst and review by others.

C.2.2   Types of Questions

EVNTRE treats eight types of questions, differentiated by the dependencies on other questions and the source of quantification information (supplied by the analyst or calculated from information determined previously). The eight types of questions are:

Type 1. This is the most simple type of event tree question -- the branch point probabilities are supplied by the analyst and are independent of other events in the tree. Type 1 questions are typically used to determine the initial conditions for the analysis. A Type 1 question might be: "What is the status of the containment sprays at the start of the core damage?" Such a question might have three branches or outcomes: sprays operating, sprays failed, or sprays not failed but unavailable (e.g., due to power loss). The quantification of this question, that is, the determination of the branch probabilities, is determined by the input from the systems analysis in the form of the plant damage state (PDS) specification.

Type 2. A Type 2 question is similar to the Type 1 question except that the branch probabilities used depend on the branches taken at one or more previous questions. This is accomplished by case structure in the tree. For each case, a logical expression involving one or more branches at a previous question is defined. If the path through the tree up to that point satisfies the conditions of the case, i.e., if the specified branches were taken, then the branch probabilities for that case apply. Most of the questions in each APET are Type 2 questions. For example, a Type 2 question might be used to make the probability of ignition for a combustible gas mixture dependent on whether electric power is available and whether the sprays are operating.

Type 3. A Type 3 question is similar to a Type 1 question in that it is independent of previous questions, but differs in that one or more parameter values are defined in Type 3 questions. Type 3 questions are used to define parameters that do not depend on the path through the tree, for example the containment failure pressure.

Type 4. A Type 4 question is similar to a Type 3 question except that the branch probabilities and parameter values depend on the branches taken at one or more previous questions. This is accomplished by case structure in

the tree. For example, a Type 4 question might be used to define different values for the parameter representing pressure rise at vessel failure depending on the amount of water in the reactor cavity at vessel breach.

Type 5. A Type 5 question is independent of all previous questions; the branch point probabilities are calculated based on the values of one or more parameters. Multiple parameter values may be combined in one of four simple ways (minimum, maximum, sum, or product) or a user function may be called to perform more complex manipulations. The user function is a FORTRAN subprogram supplied by the analyst that is executed during evaluation of the tree. It is compiled and linked with the rest of the EVNTRE code before the tree is evaluated. Code words in the question allow different portions of the user function to be evaluated at different Type 5, 6, 7, and 8 questions in the event tree. The way in which branch probabilities are determined for Type 5, 6, 7, and 8 questions is explained below. A Type 5 question might be used to determine whether the containment failed by adding a pressure rise to the base pressure and comparing the sum to the failure pressure.

Type 6. A Type 6 question is identical to a Type 5 question except that it contains case structure and so is dependent on the branches taken at previous questions. Say the pressure rise calculation for hydrogen deflagration in the user function differs depending on whether the containment atmosphere is saturated or dry. A Type 6 question might be used to evaluate one portion of the user function when the sprays are operating and a different portion of the user function when the sprays are not operating.

Type 7. A Type 7 question is similar to a Type 5 question except that parameter values are defined as well.

Type 8. The Type 8 question is the same as Type 6 question except that parameter values are defined as well.

In Type 5, 6, 7, and 8 questions, the branch probabilities are calculated by EVNTRE based on parameter values. If the parameter values are to be combined to obtain the minimum, maximum, sum, or product, the resultant value of this operation is used to determine the branch probabilities. The user function is a FORTRAN FUNCTION subprogram, so a value is returned from the subprogram in the variable that has the same name as the FUNCTION subprogram. When a user function is evaluated at a Type 5, 6, 7, and 8 question, it is this value that is used to determine the branch probabilities.

Branch probabilities are determined in one of four ways for Type 5, 6, 7, and 8 questions. The method is specified by the user in the question definition. The four types of comparison are: EQUAL, NORMAL, THRESH, and GETHRESH.

o   EQUAL. When the EQUAL method of determining branch probabilities is used, the result of the combination operation or the FUNCTION value is used directly as the probability for

Branch 1. The complement of this value is used as the probability for Branch 2. Only two branches are allowed if this method of branch probability determination is used. The result of the combination operation or the FUNCTION value must have a value between 0.0 and 1.0.

- NORMAL. The probability of Branch 1 is the probability that the result of the combination operation or the FUNCTION value will exceed a value drawn at random from a normal probability distribution. The comparison parameters provided in the definition of the question are the mean value and standard deviation of the normal distribution. The complement of the probability of Branch 1 is used as the probability for Branch 2. Only two branches are allowed if this method of determining the branch probability is used.

- THRESH. The result of the combination operation or the FUNCTION value is compared to a supplied threshold value. If the result of the combination operation or the FUNCTION value is greater than the threshold value, the probability of Branch 1 is 1.0. If the result of the combination operation or the FUNCTION value is less than the threshold value, the probability of Branch 1 is 0.0. The probability of Branch 2 is the complement of the probability of Branch 1. Only two branches are allowed if this method of determining the branch probability is used.

- GETHESH, allows the result of the combination operation or the FUNCTION value to be placed in discrete ranges. A branch is defined for each range desired and the result is compared to a series of threshold values to determine the appropriate range or branch. The threshold values must appear in descending order. If there are N threshold values in the series, the question must have N+1 branches. If the result of the combination operation or the FUNCTION value exceeds the nth threshold, but not the $n-1^{th}$ threshold, the nth branch is assigned a value of 1.0 and all other branches are assigned a value of 0.0. If the result of the combination operation or the FUNCTION value does not exceed any of the threshold values, the last branch is given a probability of 1.0. If the result of the combination operation or the FUNCTION value exceeds all of the threshold values, the first branch is given a probability of 1.0.

C.2.3   Case Structure

In the event trees, dependency on the branches taken at previous questions is expressed through case structure for questions of Type 2, 4, 6, and 8. Examples from the Surry APET for Type 2 questions will be used to illustrate case structure. The entries for a case occupy four lines in the computer input file for a Type 2 question. These lines for Case 1 of Question 21 are:

```
     1          8                          $ Case 1: Had power initially
                1                          $  - have power now.
             B-ACP                         $ If have SG-HR, must have B-ACP
             1.000        0.000       0.000
```

Question 21 determines whether AC power is available in the early period. There are three branches, with mnemonic identifiers E-ACP, EaACP, and EfACP:

> Branch 1: E-ACP - AC power is available in this period
> Branch 2: EaACP - AC power is not available in this period but may be restored in the future
> Branch 3: EfACP - AC power is irretrievably failed

The entries to the right of the $ are comments which are ignored when EVNTRE evaluates the APET. The first line for Case 1 of Question 21 indicates that Case 1 has 1 condition, and that it concerns Question 8. The second line indicates that Branch 1 must have been taken at this question, and the third line gives the mnemonic identifier for that branch. The fourth line gives the branch probabilities to be used if the conditions for this case are satisfied. So Case 1 of Question 21 indicates that, if Branch 1 was taken at Question 8, i.e., if AC power was initially available, then all the probability is assigned to Branch 1 here, that is, AC power is available in the early period.

A case may have more than one condition: the four lines comprising the third case for Question 21 are:

```
     2         10                10         $ Case 3: No Initial AFW - TRRR-RSR
                2    +            3         $ Recovery Period = 0.5 to 2.0 hours
             SGaHR   or       SGfHR         $ Remaining cases have SGdHR -
             0.565         0.435      0.000 $ AFW initially available
```

The conditions for this case are that either Branch 2 or Branch 3 was taken at Question 10. The mean probability that AC power is recovered in this period for this type of accident is 0.565. The + in the second line indicates a logical OR to EVNTRE: either|condition is sufficient for the case to be utilized. The + is required, since the default, no logical indicator between the branch numbers, is that both conditions are required for the case to be utilized. The "or" in the third line is included as an aid to reviewers; the third line contains only mnemonics and is ignored by EVNTRE when the tree is,processed. Provision is made for the mnemonic branch identifiers as an aid to the analyst and reviewers.

If both conditions are required for a case to be utilized, the case entry looks like Case 5 of Question 21 of the Surry APET:

```
     2          1                11         $ Case 5: Initial AFW & S3 Break
                3    *            2          $ Secondary Not Depressurized
             Brk-S3  &       noScDePr        $ Recovery Period = 4 to 5.5 hours
             0.394         0.606      0.000
```

The conditions for this case are that both Branch 3 at Question 1 and Branch 2 at Question 11 were selected. The mean probability that AC power is recovered in,this period for this type of accident is 0.394. The * in the second line

C.6

indicates a logical AND to EVNTRE: both conditions are required for the case to be utilized. The * is not required, since the default, no logical indicator between the branch numbers, is AND. The & in the third line is included merely as an aid to reviewers.

In interpreting the case structure of an APET, it is important to note that the cases are considered in the order they appear in the tree and that the case utilized is the first case for which the conditions are satisfied. Thus, the order of the cases is very important where a path satisfies the conditions for more than one case. As an example, consider two cases: A and B. Case A has two conditions, CX and CY, related by a logical OR: [CX OR CY]. Case B has the same two conditions but they are related by a logical AND: [CX AND CY]. If Case A is placed first, Case B will never be selected since all the paths which satisfy the conditions for Case B also satisfy the conditions for Case A. If Case B is placed first however, the paths which satisfy conditions CX and CY will be selected for Case B.

More complicated Boolean logical expressions can be constructed for a case by means of parentheses. Case 1 of Question 23 is an example of such a case:

```
5      22            1              1              18             16
        1    +       4    +     (     2   *   (       1    +         1  )  )
      EBD-A   or   Brk-V   or   ( Brk-S2   &   (  PrmDePr   or   PORV-StO )  )

      0.000        0.000        0.000             1.000
```

The comment statements have not been included for this case. Question 23 has four branches. Although conditions with mixed OR and AND logic will be treated by EVNTRE in the default mode, it is suggested that the analyst always include the parentheses to make the logic of the case unambiguous and explicit. Only the parentheses in the second line are required; the parentheses in the third line, which is ignored by EVNTRE, are included to aid the analyst and reviewer.

The logic of Case 1 of Question 23 is such that all the probability will be assigned to Branch 4 if one of three conditions is satisfied. The first condition is that there was a large initiating break inside containment (Branch 1 of Question 22). The second condition is that there was a large initiating break in an interfacing system (Branch 4 of Question 1 - Event V). The third condition is that a small (S2) break occurred (Branch 2 of Question 1) and the PORVs are open. The PORVs may be either opened deliberately (Branch 1 of Question 18) or stuck open (Branch 1 of Question 16).

The last case in Type 2, 4, 6, and 8 questions is always an "otherwise" case. That is, if the path through the tree does not satisfy the conditions for any of the other cases, the branch probabilities in the last case are applied. In developing the logical structure of the event tree, the analyst should always note what paths are expected to fall into the otherwise case, and then check during debugging to make certain that only those paths are being treated by the otherwise case. It occasionally happens that paths not considered by the analyst end up in the otherwise case when it is not appropriate for them to do so.

C.2.4   Sampling and File Structure

A general familiarity with the types of files required by EVNTRE as input and produced by EVNTRE as output is required for an appreciation of some of the steps in the development, quantification, and evaluation of the large, complex event trees used to perform the accident progression and containment response analyses for NUREG-1150. This section provides only a summary of the EVNTRE file structure; more detail may be found in the EVNTRE reference manual.[2]

Two input files are required to run EVNTRE: a keyword file and a tree file. The keyword file contains keywords which control the operation of the program. Keywords select the mode of operation, set the path cutoff probability, provide the names of the other input files and the output files, decide whether the tree is to be completely or partially processed, and determine which reports are to be generated.

The tree file contains the event tree itself. The event trees developed for this project are so large that they cannot be drawn in any conventional form. Portions of the APETs can be expressed graphically, but the entire tree exists only as the EVNTRE input file. The tree file has a certain form and format specified by EVNTRE and described in the EVNTRE reference manual. Since the complete tree exists in no other form, references to the event tree or the APET generally mean this input file, in either computer media or printed form.

The process of grouping together similar paths through the event tree is known as "binning;" the input file to EVNTRE which contains the grouping instructions and defines the "bins" is known as the "binner." EVNTRE will also sort the resulting bins if instructed to do so; if sort instructions are present, they are included in the binner. If the paths through the tree are not to be binned, no input binner file is required. The tree is sometimes evaluated without binning during development and debugging, but is normally evaluated with a binner. Binning is required because the APETs used for NUREG-1150 have far too many paths through them for each path to be examined individually by the analyst or for each path to be considered individually in the source term analysis. The output bins from the APET form the interface between the accident progression analysis and the source term analysis as explained in Section 6.4.

As explained in Section 3.3, uncertainty is treated by a sampling approach. That is, the tree is evaluated many times, with different values for the quantities important to the uncertainty in risk. EVNTRE incorporates a replacement feature to facilitate APET evaluation in this mode. When operated in the sampling mode, EVNTRE requires two additional input files: one tells EVNTRE which branch probabilities and parameter values in the tree to replace, and the other file contains the replacement values. The file which indicates which quantities in the tree to replace is known as the sample definition or pointer file. Following a few control entries, the pointer file contains an entry, "pointer," for each branch probability or parameter value to be sampled.   Since the branch probability must sum to 1.0 exactly for each case of each question, the complement of the replacement value is placed in the second branch defined in each pointer as explained in the EVNTRE reference manual.

The sample file or sample input vector file contains the replacement values. If 53 values are being replaced in a sampling mode evaluation involving 100 observations, the pointer file contains 53 pointers. The sample file contains 100 sets or vectors of 53 values each. In the first observation the first vector of 53 values is used, in the second observation the second vector of 53 values is used, and so on. In actual practice, each sample vector might have more than 53 values, and the pointer file would indicate that the extra values were not to be used. However, there must be a pointer file entry for each entry in the sample vector.

EVNTRE has the capability to produce four types of output files. The echo file is an annotated reproduction of the tree and binner input files. It is useful when developing or debugging the tree. The bin file contains the output bins, with a probability for each. The accident progression bins are identified by a string of letters--one letter for each characteristic of the binner. This is the file that is manipulated for further use and contains the information used to form the initial conditions for the source term analysis. A similar file, with each bin identified by the mnemonic identifier for each attribute instead of a letter may also be printed, but this file is so lengthy that it is used only for tree development and debugging. The fourth output file is known as the frequency report. This file contains the average branch probabilities over all paths for each branch for each question, broken down by case. The frequency report is used to examine the results of tree evaluation in detail. It is probably the most useful output from EVNTRE for APET development and debugging. The best check of the tree logic is generally to run the tree for a number of different but very specific initial conditions, and examine the frequency report carefully for each question. The output bins with non-zero probability should also be reviewed in detail during this stage of tree development.

C.3   Event Tree Development

Before the event tree for the accident progression and containment response analysis can be developed, the analyst has to know how core damage accidents progress in nuclear power plants of the type being analyzed, and has to be aware of the constraints placed upon the APET by the interfaces. The APET is of no use if it doesn't accept the results of the accident frequency analysis in the form they are generated, and if it doesn't produce results in a form suitable for use by the subsequent source term analysis. With a good knowledge of accident progression and the interfaces, the analyst is then prepared to define the major time periods for the analysis and then to develop the tree in detail.

C.3.1   Information Required for Event Tree Development

An event tree that represents the accident progression and containment response in a satisfactory manner can only be developed by an analyst who is familiar with the processes and events involved. A great deal of the contribution of the analyst who develops the tree comes from his decisions of the events and processes to include, those to leave out, and level of detail in which each should be treated. While the analyst cannot be expected to be an expert with detailed knowledge on each process and event, he must have a general understanding of all the processes and events that take place during and after

core melt. In general, this means that the analyst must accumulate and digest a large amount of information before starting to develop the event tree.

A great deal of information is utilized in the accident progression and containment analysis. The event tree summarizes the available information into an integrated logical structure that allows a probabilistic delineation of the possible paths that the accident might take following the onset of core damage. While the event| tree does not mechanistically model the processes such as thermohydraulic flows or concrete attack by molten core material, it represents these processes and their outcomes in a general fashion through branch definitions and probabilities and through the determination of parameter values. Relatively simple calculations, such as the determination of adiabatic pressure rise due to hydrogen deflagration, can be computed in the user function, but the event tree is not meant to be, and cannot be, a detailed mechanistic model of the accident progression events and processes. In a mechanistic code, the reactor coolant system pressure, for example, would be calculated as a function of time by a time step process. In the APETs, reactor coolant system pressure is usually placed into one of a few, typically four, pressure ranges for each of several time periods.   .

In order to synthesize all this information in the event tree, the analyst has to be aware of it. Part of the accident progression and containment analysis process is the collection of information relevant to the response of the plant to the accident. This includes not only design and as-built information about the reactor coolant system, the containment structure, and safety systems that operate to mitigate the effects of an accident, but also includes results of previous analyses of the response of this and similar plants to core damage accidents as well as reports of experiments on relevant phenomena. The information to be obtained includes:

- Results of detailed (e.g., CONTAIN[3]) and integrated (e.g., STCP[4] or MELCOR[5]) code calculations for partial and complete accident sequences;   '

- Studies of particular phenomena such as hydrogen combustion with detailed, specialized codes,

- Previous risk assessments on this or similar plants, and

- Reports of experiments.

The results of code analyses of similar plants often contain a lot of useful information that is applicable, so the information collected should not be restricted to the specific plant being considered.

The nature of the event tree also depends on the interfaces with the preceding and subsequent PRA tasks. The APET must utilize the results of the accident frequency analysis as initial conditions, and the results of evaluating the APET are used as the initial and boundary conditions for the source term analysis. The interfaces in the entire risk analysis are presented in Chapter 4, and this material need not be repeated. The use of PDSs to form the interface with the

C.10

accident frequency analysis are treated in some detail in Chapter 5. The definition of accident progression bins (APBs) to form the interface with the source term analysis is discussed in Section 6.4. If the development of the event tree is to proceed in an orderly and efficient manner, the general nature and most of the details of both interfaces should be set before the task is begun. In general, the event tree has to consider the development of all the important accidents determined by the accident frequency analysis, but should not consider others. Similarly, the APET must provide all the information required by the source term analysis, but in most cases there is no point is providing information that is not utilized in one of the subsequent analyses. The task of developing the tree with sufficient detail to generate the information required but without superfluous detail is made easier if the interfaces are defined early in the task.

C.3.2   Definition of Time Periods

One reason the APETs developed to perform the accident progression and containment response analyses for NUREG-1150 are so large is that the accident progression is divided into several time periods, and important events and processes are considered in each time period. For example, questions about the availability of AC power and the operation of containment heat removal appear several times in the event tree because they are asked in each time period. One of the first steps in the tree development process is the selection of these time periods.

The time periods follow more or less directly from the progression of the accident itself, although a certain amount of subjectivity is involved in the choice of boundaries between periods and whether a certain period should be subdivided. The major event in the core degradation process is vessel breach, which usually occurs by failure of the lower head. Therefore the questions in the event tree may be placed into six major groups:

> Initial Conditions
> Period Before Vessel Breach
> Period Around Vessel Breach
> Period After Vessel Breach
> Very Late Period
> Summary Questions

Only four of these groups of questions represent time periods. These groupings are only suggested grouping of questions that will be found in most trees. The list is not immutable, and it is often necessary to expand this list somewhat to accommodate the analysis of a particular plant. For example, the analyst for a plant that has core vulnerable PDSs may wish to create an additional group for the questions that resolve the core vulnerable situation. Or the analyst may wish to divide the period after vessel breach into an early CCI period and a late CCI period. The time periods are not intended to be equal in duration, but may be roughly equal in the number of questions involved. The period around vessel breach is fairly short, perhaps only a few minutes, but many important events occur at this time and the containment is particularly likely to fail at this time, so this period may warrant as many questions as another period which lasts for several hours.

The questions that determine the initial conditions at the onset of core damage appear first in the tree. The initial conditions are set by the definition of the PDS, and generally there is one event tree question for each characteristic of the PDS. If there are no core vulnerable PDSs, the second group of questions treats the period before vessel breach. The questions in this group concern the core degradation process in the vessel, the possibility of avoiding vessel breach, the status of important safety systems, and threats to containment integrity before vessel failure. The response of the reactor coolant system to the stresses created by core degradation are important in this period. For example, heat from the melting core could cause the hot leg to fail, thereby reducing the pressure in the reactor coolant system and changing the nature of the events at vessel breach. Vessel breach may be avoided if core coolant injection and heat removal can be re-established before the core melt has progressed so far that vessel failure cannot be prevented. In these studies, this was often termed core damage arrest, and implies the attainment of a safe, stable state with the vessel intact as at TMI-2. The containment may fail before vessel failure due to hydrogen combustion events or due to steam pressure if there is no heat removal from the containment.

The period around vessel breach, although short, requires many questions to treat events such as the relocation of the core, the large stresses that may be placed upon the containment by phenomena that may accompany vessel failure such as vessel blowdown, steam explosions when the core material enters water in the reactor cavity, and direct containment heating due to the dispersal of hot core particles throughout the containment by the blowdown. In the period after vessel breach, the main concern is the interaction of the molten core with the containment structure. In some containment designs this is largely restricted to the interaction of the core with the concrete in the basemat, but in other containments different interactions are possible. The questions in the late period usually concern events that happen after the initial rapid phase of the core-concrete interactions (CCI). The main concern here is that the containment may eventually fail due to the generation of non-condensable gases or that it may fail from steam pressure if containment heat removal is not restored. A very late period is often added to include questions about the eventual fate of the containment if containment heat removal is not restored after a few days.

Each group of questions is discussed in the following subsections.

C.3.3   Initial Conditions

In past PRAs, it was common to develop a relatively small event tree, typically called containment event trees, for each type of accident. The initial conditions were implicit for these event trees. In the analyses performed for NUREG-1150, a single large event tree was developed for each plant. As this event tree or APET has to be able to treat all accident scenarios of interest, the initial conditions for the accident progression and containment response analysis must be determined explicitly. This is usually done in the first set of questions in the tree. These questions essentially take the information contained in the PDS and make it available in the event tree. By setting the branch probabilities in the initial condition questions, the analyst determines what type of accident is being analyzed in the remainder of the event tree.

For example, the first PDS characteristic for the Surry plant concerns the RCS condition at the onset of core damage. This characteristic can take on seven values:

A	-	large or intermediate size break in the RCS
S_2	-	small break in the RCS
S_3	-	very small break in the RCS
V	-	large break in an interfacing system
T	-	transient event (no pipe break)
G	-	steam generator tube rupture (SGTR) with the secondary system relief valves reclosing
H	-	SGTR with the secondary system relief valves stuck open

These possibilities for the first PDS characteristic are reflected in the first question of the Surry APET; Size and Location of the RCS Break when the Core Uncovers? There are six branches:

1	Brk-A	-	large or intermediate size break in the RCS
2	Brk-S2	-	small break in the RCS
3	Brk-S3	-	very small break in the RCS
4	Brk-V	-	large break in an interfacing system
5	B-SGTR	-	steam generator tube rupture
6	B-PORV	-	transient event, PORV(s) open

For the SGTR initiators, whether the secondary system relief valves reclosed is determined in a subsequent question. For the transient initiators, there is no pipe break, but one or more PORVs must be open to allow the escape of the steam being generated as the core coolant boils away. The parallel structure between the first PDS characteristic and the branches for Question 1 is evident. Most of the initial condition questions are constructed in a similar manner.

If the event tree is to be evaluated for a single PDS, the branch probabilities for the initial condition questions are set to 0.0 or 1.0 to indicate the appropriate PDS. This is typically done when the tree is being checked out and debugged. When the APETs are evaluated in a production mode, all the PDSs must be treated. This may be done in one of three ways:

1. Make a separate tree for each PDS and "stack" them;
2. Condense the PDSs into a smaller number of groups, make a tree for each group, and "stack" them; and
3. Use fractions between 0.0 and 1.0 for the branch probabilities in the initial condition questions so that one tree can treat all PDSs.

"Stacking" refers to the process of placing one tree behind another in the EVNTRE input file; when EVNTRE finishes processing one tree, it goes on to the next so all PDSs would be treated in successive EVNTRE computer runs. The trees are identical except for the branch probabilities for the initial condition questions. For most plants, there were between 20 and 40 PDSs, so option 1 above would require 20 to 40 copies of the event tree with different branch probabilities for the initial condition questions.

The computer processing times do not appear to be a strong function of the method chosen for treating all PDSs since the same number of paths through the tree have to be considered in each case. The choice between these options is a matter of convenience for the analyst. For the NUREG-1150 analyses, the PDSs were grouped by initiating event, so option 2 above was utilized. For Surry, for example, there were 25 PDSs which were above the cutoff frequency of 1.0E-7/R-yr, and they were placed into seven PDS groups for the accident progression and containment response analysis:

1. Slow Station Blackout
2. LOCAs (pipe breaks)
3. Fast Station Blackout
4. Event V (break in an interfacing system)
5. Transients
6. ATWS (transient followed by scram failure)
7. SGTR (steam generator tube rupture)

Placing the PDSs into groups for evaluation means that some of the initial condition questions will have branch probabilities between 0.0 and 1.0. For example, say there were only two SGTR PDSs, and the PDS group with the secondary SRVs reclosing is twice as likely as the PDS with the secondary SRVs stuck open. Then the question that determines whether the SRVs are closed or open would have a probability of 0.667 for the branch that indicates that the SRVs have reclosed and a probability of 0.333 for the branch that indicates that the SRVs are stuck open. Some PDS groups used in the plant analyses for NUREG-1150 had only one or two PDSs, and so the initial conditions questions could be treated in a fairly simple manner. Other groups had five to ten PDSs, and the treatment was more complex. Further discussion is warranted only for a specific plant. The PDS groups utilized are presented in Section 2.2 of the plant volumes[6-10] and details of the treatment of the initial conditions questions when the APET is evaluated in the sampling mode may be found in Appendix A.3 of the plant volumes.

C.3.4   Period before Vessel Breach

The period before vessel breach is often termed the "early" period in the APETs. There is no fixed length for this period since it extends until the vessel fails, and the time from the onset of core damage to the failure of the vessel depends on the type of accident. Thus, the duration of this period may range from an hour or less to several hours.

The questions included in the early period concern the core degradation process in the vessel, the possibility of avoiding vessel breach, the status of important safety systems, and threats to containment integrity before vessel failure. The response of the reactor coolant system to the stresses created by core degradation are important in this period. The pressure in the reactor coolant system during this period is important since it affects the rate of release of hydrogen from the melting core and rate of release of radionuclides to the containment. The reactor coolant system pressure at the start of the period is known from the initial conditions, which are reflected in the PDS. Changes in the pressure during the period are important since the pressure in the vessel when it fails largely determines the magnitude of the containment loading at that time.

For the PWRs, a number of questions in the early period concern the possibility that the core degradation process will increase temperatures enough to affect the structural integrity of the primary coolant system before direct failure of the lower head of the vessel. The temperature-induced failure modes considered are: failure of the hot leg or pressurizer line, rupture of a steam generator tube, failure of a reactor coolant pump seal, and failure of the PORV to reclose. In addition, deliberate opening of the PORVs by the operators is considered.

An important feature of the APETs developed for NUREG-1150 is the inclusion of the possibility of reflooding the core before a serious threat to the integrity of the vessel. Vessel breach may be avoided if core coolant injection and heat removal can be re-established before the core melt has progressed so far that vessel failure cannot be prevented. In accident progression analyses performed for NUREG-1150, this was usually termed core damage arrest, and implies the attainment of a safe, stable state with the vessel intact as at TMI-2. There is a great deal of uncertainty in the timing and needs for successful cooling during this phase of the accident, and these uncertainties are reflected in the event tree model. The trees only consider this possibility for accidents involving loss of electrical power, where equipment is unavailable due to lack of power rather than failed and there is the possibility of recovery when power is restored. (The loss of power accidents were important contributors to the core damage frequency of each of the plants studied in this program.) The questions for core damage arrest include questions about the recovery of offsite electrical power, the operability of systems to inject water to the core, and questions to determine the probability that injection is restored before so much of the core is molten that vessel failure cannot be averted.

The containment may fail before vessel failure due to hydrogen combustion events or due to steam pressure if there is no heat removal from the containment. For some types of containments, many questions in this period are required to track hydrogen production before vessel failure, determine the probability of hydrogen combustion, and decide whether a hydrogen combustion event will fail the containment. While the operability of all safety systems is of interest, the operability of containment pressure suppression and cooling systems is of particular concern since their operation has a direct effect on the possibility of hydrogen combustion and containment failure. For multi-compartment containments, hydrogen, oxygen, steam, and inert gas concentrations may have to be computed for more than one compartment.

The sequence of questions to treat hydrogen, production and combustion and the threat to containment integrity in this period might be as follows for a single compartment containment:

>   Determine hydrogen production in vessel;
>   Determine fraction which escapes to the containment;
>   Determine operability of pressure suppression and containment heat removal systems;
>   Determine steam concentration and base containment pressure as a function of which pressure suppression and containment heat removal systems are operating;
>   Call user function to compute gas concentrations and determine whether the containment atmosphere is flammable;

Determine probability of ignition;
Call user function to compute type of combustion (deflagration or
detonation) and pressure rise;
Compare sum of base pressure and pressure rise to containment
failure threshold and determine whether the containment fails.

The exact number of questions and their type is at the option of the analyst.
All the computations might be performed in one call to the user function, for
example, instead of the two shown above. Oxygen and inert gas amount and
concentration might be expressed explicitly in the tree as parameters, or kept
as FORTRAN variables in the user function. The schemes used to treat hydrogen
production and combustion before vessel breach for Sequoyah and Grand Gulf are
presented in detail in the plant volumes of this report.[8,9] Hydrogen production
before vessel breach was not considered a serious threat to the containments of
the other three plants considered in this program.

Core vulnerable situations may be resolved in the early time period, or a special
block of questions may be defined for this purpose. Core vulnerable accidents
are those where the systems analysis ends with a successful cooling of the core,
but continued cooling is dependent on the response of the containment. Feedback
from the accident progression analysis to the systems analysis is needed to
resolve these sequences into those that cause core damage and those that do not.
A typical core vulnerable accident sequence has heat being successfully removed
from the core to the containment, but no heat removal from the containment to the
environment. The continuation of core cooling indefinitely depends on if and
when containment heat removal is restored and if and when the containment fails.

Of the five plants analyzed for NUREG-1150, only Peach Bottom had core vulnerable
PDSs. The plant volume for Peach Bottom[7] should be consulted for specific
details of how core vulnerable situations may be resolved. In general the core
vulnerable questions are placed right after the questions that determine the
initial conditions. These question consider the effects of no containment
cooling in terms of pressures, temperatures, and threat to containment integrity
and treat possible recovery actions such as venting the containment. The adverse
effects of containment failure or venting must be considered. For example,
containment depressurization could fail the pumps supplying water to the core by
reducing the pump suction head.

C.3.5 Period around Vessel Breach

The time period during and immediately after vessel breach is important because
of the high probability of containment failure and radiological release. There
is no fixed length for this period, but it typically extends from a minute or two
before vessel failure to several tens of minutes after vessel failure.

For many types of reactor core melt accidents, the greatest threat to containment
integrity comes from the pressure loading that accompanies failure of the vessel
lower head. The determination of the pressure in the reactor coolant system just
before vessel breach may be placed in this period or as one of the final
questions of the preceding period. The questions placed in this time period
usually determine the type of vessel failure, the magnitude of the pressure rise
in the containment, the reaction of the containment to the stresses placed upon

C.16

it, and any effects on the containment heat removal and pressure suppression systems.

The bottom head of the vessel may experience gross failure or a penetration may fail first and then ablate to form a larger hole. The pressure in the vessel determines whether the core material is forced out in a jet or flows out primarily due to the force of gravity. Questions in this time period determine the type and size of lower head failure and the composition of the core material released.

Questions in this section of the APET also determine the loads placed upon the containment by the events at vessel breach. In addition to the steam and hydrogen released in the vessel blowdown, molten core materials encountering water in the reactor cavity may generate large amounts of steam. Direct containment heating may also contribute significantly to the containment pressure rise. If the vessel fails at high pressure, the jet of molten core material that results is likely to spread small particles of hot core material throughout the containment. Heat transfer from these particles can cause a significant increase in containment pressure. Hydrogen released before or at vessel failure may ignite at vessel breach and contribute to the pressure rise. In computing the pressure rise due to hydrogen combustion at vessel breach, care must be taken to account for the hydrogen and oxygen consumed in burns before vessel failure, if any. This may be accomplished by using parameters to represent the quantities of hydrogen and oxygen in the containment (or in each compartment) and updating and redefining these parameters in the section of the user function that is evaluated in each time period.

In the accident progression and containment response analyses performed for NUREG-1150, the containment pressure rise at vessel breach was generally not calculated in a user function. There was no detailed, mechanistic code which simulated all the phenomena that occur at vessel breach to the satisfaction of the experts convened to review the situation. And, in the time available, it did not appear feasible to develop a small FORTRAN subprogram that would mimic the results of one of the more advanced containment response codes (e.g., CONTAIN[3]) in a way that would be generally acceptable. Instead, an expert group was used to define probability distributions for the pressure rise at vessel breach for each plant for a number of situations (e.g., high vessel pressure, small hole, etc.). These distributions were then used with the sampling capabilities of EVNTRE described above to determine the pressure rise at vessel breach for each observation in the distribution. This allowed the effects of all the pressure rise mechanisms to be accounted for, even though widely accepted models may currently be lacking for some of them. The experts were aware of the results of all the detailed, mechanistic codes, and relied on those results they considered the most representative when forming their pressure rise distributions. In this way, the latest detailed, mechanistic code results for containment pressure rise were used in the events trees, but their utilization was indirect.

Containment failure mechanisms which occur at vessel failure and which are specific to a plant or class of plants are also considered in this time period. Questions are included to treat events such as the failure of the seal table at Sequoyah or direct contact of the melt with the drywell wall at Peach Bottom. Failure of the seal table at Sequoyah may occur due to cavity pressurization or

direct impingement by core particles in a high pressure melt ejection event. The outer wall of the seal table room at Sequoyah is formed by the steel containment shell, so the accumulation of sufficient core debris in the seal table room against the outer wall could melt through the containment pressure boundary. At Peach Bottom, which has a BWR Mark I containment, if the molten core material flows far enough across the floor of the drywell, it will encounter the steel shell which forms the pressure boundary, and may melt through it.

C.3.6   Period after Vessel Breach

The events of primary interest in the period after vessel failure are the interactions of the molten core material with the containment. The typical process in this period is the attack of the core on the concrete basemat which forms the floor of the reactor cavity. In some containment designs, other events may also be of interest. For example, if the cavity is small and its walls form an important part of the containment structure, erosion of the concrete walls by the molten core could cause structural failure of the vessel supports or even the containment itself. There is no fixed length for this period; it typically extends until the bulk of the core-concrete interaction (CCI) is complete and so has a duration of several hours.

In addition to questions about CCI, this section of the tree includes questions about the supply of water to the cavity and the possibility of debris coolability, the operation of containment heat removal and pressure suppression systems, the amount of additional combustible gas (hydrogen and carbon monoxide) generation, the flammability of the containment atmosphere, the probability of ignitions, and the containment response to any loads placed upon it. The questions concerning atmospheric composition, combustion, and containment response are generally similar to those in earlier time periods that treat the same phenomena.

C.3.7 Very Late Period

Typically, a tree includes questions to account for slowly-evolving accidents, such as a pressure increase in the absence of containment heat removal that might take tens of hours or days to reach levels that would threaten containment integrity. Another long-term event of interest is the restoration of containment sprays (or other cooling systems) after many hours. The rapid condensation of steam might cause the containment atmosphere to pass from inert to flammable, thus introducing the possibility of hydrogen ignition and late containment failure. Failure of containment by meltthrough of the basemat is also possible in this time period. The questions needed to determine these types of late containment failures are placed in this time period.

The late period questions are generally only important for event tree pathways in which there is no previous failure or bypass of the containment. The hydrogen combustion questions in this time period are much like those in the preceding time period. For some containment designs, in the absence of containment heat removal, whether an intact containment will fail by the continual buildup of temperature and pressure before the basemat melts through is not well known. The offsite risk consequences of either failure mode are low, however, with respect to the consequences when the containment fails at or before vessel failure.

C.3.8   Summary Questions

Summary questions are often placed at the end of the event tree. These questions are usually placed here for the convenience of the analyst or to reduce the complexity of the binner. Summary questions may also appear elsewhere in the tree, but they are considered part of the time period in which they occur. The summary questions at the end of the tree typically identify the chief outcomes, basically the containment failure mode and location, and the time of failure.

C.3.9   Development of the Binner

Placing the paths through the event tree into groups or bins is required to reduce the paths through the tree to a manageable set. The set of instructions to EVNTRE that defines the bins is known as the "binner." The definition of accident progression bins (APBs) to form the interface with the source term analysis is discussed in Section 6.4. The EVNTRE User's Guide[2] describes the input format for the binner in detail.

The primary output of an evaluation of the APET by EVNTRE is a list of bins with a probability for each. It is the bins that are passed on, perhaps after some manipulation, to form the initial and boundary conditions for the source term analysis. A bin appears as a string of letters. Table 6-5 lists some bins for the Surry analysis. The Surry binner has 11 characteristics, so there are 11 letters in the string that defines a bin for Surry. Characteristics and attributes as used in the binner are defined in Section 6.4. The binner for each plant is listed and described in Appendix A of the plant volume.[6-10]

It may be helpful to consider the binner as representing the branches taken in a reduced event tree. The characteristics of the binner can be thought of as summary questions. For Surry, for example, there would be 11 summary questions, listed in Table 6-2, and the first question would have the branches listed as attributes in Table 6-3.

The binner lays out the Boolean logic expressions that define the bins. The form of the cases that define the conditions for an attribute is very similar to the form used for cases in the event tree itself. An important difference is that the binner does not allow an "otherwise" case. That is, the conditions for each attribute of each characteristic must be specified. If EVNTRE comes across a path with a non-zero probability that satisfies the conditions for none of the attributes in a characteristic, an error message is generated. As with the cases for questions in the tree, if the path satisfies the conditions for more than one attribute, the first case encountered for which the conditions are met determines the attribute selected.

An example will allow the features of the binning process to be discussed in detail. The first characteristic of the Surry binner input concerns the time, and to a certain degree, the nature of containment failure. Five of the eight attributes concern the time of failure, but two concern Event V, an initial bypass of the containment due to a large interfacing system LOCA. Because of the size and timing of Event V, any subsequent failures of the containment are not apt to be important for risk. Some SGTRs, however, may release very little

C.19

radioactive material, so containment failures are important for SGTRs even though they may also result in bypass of the containment.

The first ten lines of the binner input for Characteristic 1 - Containment Failure Time, are:

```
8  8  V-Dry  V-Wet  Early-CF  CF-at-VB  Late-CF  VLate-CF  Final-CF  No-CF
4  8      71            1         19       71              $ Case 1, Attr. 8 (H)
           5  + ((      5  +      1  ) *   4    )          $    No CF or SGTR with
         noCF or ((B-SGTR or E-SGTRS3  ) & Bypass )        $    no other CF
2  1       1       .   14                                  $ Case 2, Attr. 1 (A)
           4  *        2                                   $    V-Dry
         Brk-V  &     V-Dry
2  2       1           14                                  $ Case 3, Attr. 2 (B)
           4  *   .    1                                   $    V-Wet
         Brk-V  &     V-Wet
```

The format is similar to that described for the tree in Section C.2.3. As before, a $ indicates that comments follow. The first line instructs EVNTRE that there are 8 attributes, and that there will be 8 cases, and then lists the mnemonic identifiers for the 8 attributes. These are the same identifiers found in Table 6-3. The logic developed by the analyst calls for the no containment failure, NoCF, attribute to be determined first. The entries for Case 1 occupy lines 2, 3, and 4 of the ten lines reproduced above. The first entry, 4, in line 2 indicates that there are 4 conditions for this case, and the second entry, 8, indicates that Attribute 8, No-CF, applies if the conditions in this case are satisfied. Question 71, the last question in the Surry APET, is a summary question which determines if the containment failed or was bypassed. If Branch 5, NoCF, indicating no containment failure was chosen, then Attribute 8 is clearly appropriate. Since SGTRs are treated in a separate binner characteristic, accidents with only an SGTR and no other failure or bypass of the containment should also be represented by Attribute 8. This is accomplished by the last three conditions of Case 1. The SGTR can be either the initiating event (Branch 5 of Question 1) or a temperature-induced SGTR that occurred during the core melt (Branch 1 of Question 19). The requirement that Branch 4 of Question 71 was chosen ensures that there were no other containment failures or bypasses.

The Event V attributes depend upon the branches taken at Questions 1 and 14. The wet or dry refers to whether the break location in the auxiliary building is under water when the radioactive releases commence. If an accident scenario that starts with an interfacing LOCA leads to containment failure at vessel breach, the bypass is considered to be the more important pathway. Such an accident would produce a path through the event tree which would satisfy the conditions for Attribute 4 (D) and either Attribute 1 (A) or Attribute 2 (B). By placing the cases that determine Attributes 1 and 2 before the case that determines Attribute 4, the analyst has explicitly given priority to the Event V containment bypass in determining the final containment condition. The entries for Case 2 occupy lines 5, 6, and 7 above and specify the conditions for Attribute 1 (A), V-Dry and the entries for Case 3 occupy lines 8, 9, and 10 and specify the conditions for Attribute 2 (B), V-Wet. The conditions for Attribute 4 (D) occur in Case 5 and are not shown in this example.

C.3.10   Documentation

The large and complex event trees used to perform the accident progression and containment response analyses for NUREG-1150 are evaluated by EVNTRE,[2] a FORTRAN computer program. Although developed specifically for this project, EVNTRE is a general event tree processing code and is not restricted to event trees for reactor accidents. The general capabilities of EVNTRE have been described in Section C.2. Only portions of the complete APETs can be drawn out in graphical form; the entire tree exists only as the EVNTRE input file and it must be documented and reviewed in this form. The tree and binner EVNTRE input files are listed in Appendix A of each plant volume.[6-10]

Once a reviewer has become familiar with the format, the reviewer can generally understand the logic of the tree directly from the tree input file if the analyst has included sufficient comments in the file. Every effort should be made to include extensive comments in the tree file. The development of the tree may occupy some time since information discovered in the quantification effort often requires revisions to the tree structure, so the comments should be entered as the tree is developed.

A discussion of each case of each question in the tree is necessary to establish the sources for values or distributions used for all the branch probabilities and parameter values. Such a discussion is also found in Appendix A of each plant volume.[6,8,9,10] The space for comments in the tree file is limited, so this question-by-question description should expand upon the comment statements in the tree itself so that the motives for the logic structure developed are clear. As the logic typically differs from case to case, a short discussion of each case is generally warranted. The meaning of each branch should be defined in this discussion. Every parameter should be defined, with the units specified, in the question in which it is first introduced. For some questions, the quantification of the tree is the result of subsidiary analyses. These analyses must be fully documented, but the insertion of many pages of material for a single question may disrupt the flow of the question-by-question discussion of the tree. The best solution to this problem appears to be to put a short summary of the subsidiary analysis in the question-by-question discussion of the tree and reference a complete description of the subsidiary analysis elsewhere in an appendix.

A discussion of the binner on a characteristic-by-characteristic and attribute-by-attribute basis is also required. Since there is no quantification for the binner, the discussion for the binner can be more succinct than can the description of the tree itself.

The documentation of the user function can be accomplished by comment lines inserted among the executable FORTRAN statements, or by text accompanying a listing of the subprogram. In either case, a code listing must be included in the final documentation, with a clear explanation of sources of information and assumptions made. The user function is listed in Appendix A of each plant volume.[6-10]

C.4   Quantification

Before an event tree can be processed by EVNTRE, numerical values must be supplied for each branch probability and each parameter. The branch probabilities for summary questions are determined by the logic of the tree, and the branch probabilities for initial condition questions are determined by the PDSs defined by the accident frequency analysis. And in most of the Type 5, 6, 7, and 8 questions, the branch probabilities are decided by parameter values determined in previous questions. For the bulk of the questions, however, branch probabilities and parameter values must be determined. This process is called "quantifying" the event tree or the "quantification" of the event tree. The quantification task is to select branch probabilities and parameter values so that the tree is as faithful a representation of accident events as possible. The source of the values used must be recorded for traceability and documentation. Further, for those branch probabilities and parameter values that will be sampled, not just single values but distributions must be determined.

The magnitude of the task should not be underestimated. A Type 4 question with four branches, two parameters, and 8 cases requires that 88 pieces of information be developed to quantify the question -- 88 distributions if all cases, branches, and parameters are to be sampled. (A parameter value must be specified for each branch for each case, so that is 8 values per case. There are four branch probabilities for each case, but the fourth is just the compliment of the sum of the first three, so that is 3 branch probabilities per case, or a total of 11 values per case.) Some of the branch probabilities and parameter values will be default values that follow from the logic of the tree, but the point is that a lot of values or distributions for branch probabilities and parameter values have to be determined and justified.

Some questions in the tree concern the reliability of equipment or the possibility of operator actions. The branch probabilities for these questions are determined from reliability data or human reliability analysis just as the system analysis models are quantified. Similarly, the probabilities of offsite electric power recovery are determined from the curves for the probability of power recovery as a function of time that were developed for the accident frequency analysis. Each case in the power recovery questions refers to a different type of accident with a specific time period that is used to estimate the chances of power recovery in the period from the probability of recovery curves.

Questions concerning processes and events form much of the APET. The branch probabilities and parameter values in these questions are usually sampled because the phenomena that occur during core melt are the cause of much of the uncertainty in the accident progression. Expert panels were convened to supply distributions for these questions that were thought to be the most important for risk and the uncertainty in risk. For questions where expert panels were not involved, the analyst relies on mechanistic model results and experimental data to develop single values or distributions, as appropriate. In developing distributions, the analyst must take competing models into account and employ distributions wide enough so that no reasonable model of the process gives results which fall outside the distribution.

When user functions are employed to make simple calculations during the evaluation of the tree, the quantities that determine the uncertainty in the outcome should be defined as parameters in the event tree. If thus defined, the values for these quantities can be sampled from a distribution and the uncertainty propagated through the analysis. Quantities that are defined only within the FORTRAN of the user function are not available for sampling.

C.5   Evaluation and Rebinning

This section discusses the processing of the event tree by computer and the rebinning of the output produced by evaluating the APET with EVNTRE.

C.5.1 Computer Evaluation of the Event Tree

The APET may be processed by EVNTRE in a number of different ways. In general, the MODE value in the keyword file controls the way in which EVNTRE processes the APET. (See the EVNTRE reference manual[2] for a technical description of the four processing modes.) In this subsection, three general ways in which EVNTRE is used to evaluate the APET are discussed. These are the ways of evaluation that proved the most useful in the development of the event trees for the accident progression and containment response analysis and in evaluating the tree multiple times in a production fashion that supported the Monte Carlo approach to the determination of uncertainty.

The first way EVNTRE is used is to perform single evaluations of the tree during the process of tree development. In the keyword file, this is MODE 1. Only the keyword, tree, and binner files need be supplied for these runs. For convenience, these evaluations usually take place on a PC, such as an IBM PS2. These evaluations during development are typically limited to a single evaluation at a time with fixed values for branch probabilities and parameters. At this stage in the analysis, the analyst is concentrating on developing the logic of the questions and cases, and the quantification is only approximate. The binner may be changed frequently to focus on certain aspects of the tree structure. It is typical at this time to alter the branch probabilities of the initial condition questions and other questions in the tree so that the results for certain kinds of accidents can be examined in detail. There is often an effort to limit the number of paths through the tree in the evaluations during development so each bin can be reviewed individually and the frequency report is easier to understand. Evaluation time for a single run with all fixed branch probabilities and parameter values on a PC is typically a few tens of seconds for a tree with 70 to 100 questions.

The second general way in which EVNTRE is used is to evaluate the APET in the sampling mode; EVNTRE is used in this fashion for production runs when a Monte Carlo scheme is being used to treat uncertainty. For the keyword file, this is MODE 3. When EVNTRE is used in this way, more input files must be supplied, and some of the input and output files are quite large. For example, the pointer and sample files, not used when a single evaluation is performed during development, must be supplied. Although performing these evaluations on a PC may be possible, it has proved more convenient and feasible to make these runs on a computer with greater memory and file storage capabilities. At Sandia National Laboratories, sampling mode evaluations of the APETs are typically performed on VAX 8650 and

8700 computers. Other machines with equivalent capabilities may be used. Several hours on one of the VAX machines are usually required to process a tree of about one hundred questions in the sampling mode for a sample of 200 to 250 observations. The time depends on the structure of the tree, the size of the sample, the number of PDS groups processed, and the fraction of questions that have branch probabilities that are either 0.0 or 1.0 exactly.

EVNTRE is also used in a third way which is similar to that just described. It sometimes happens after the production runs are completed in the sampling mode, that the analyst wishes to look more closely at the results of the APET evaluation for one or a few observations in the sample. It is possible to accomplish this by setting MODE 3 in the keyword file and then setting the number of observations and the starting observation in the pointer file to obtain results for just the observations desired. By using EVNTRE in this fashion, it is possible to obtain detailed EVNTRE output for one or a few observations that would be too voluminous to obtain for all the observations.

It is the sampling mode, the second of the three ways of processing the APET described above, which is used for productions runs to obtain the results reported in NUREG-1150. As explained in Section 3.3, the risk analyses for NUREG-1150 used an efficient stratified Monte Carlo technique, Latin hypercube sampling,[12] to determine the uncertainty in risk. The efficiency of this sampling method meant that many fewer observations were required than would have been necessary using a purely random, unstratified Monte Carlo approach: only 200 or 250 evaluations of the tree were required. EVNTRE was designed with a multiple evaluation feature specifically for this purpose. For multiple evaluations in the sampling mode, additional files are required as explained in Subsection C.2.4. The "pointer" file, indicates to EVNTRE which branch probabilities and parameters are to be sampled, and the "sample" file provides the values for these quantities. In (Eq. 3.3) of Section 3.3, nV is the number of variables sampled for the entire risk analysis; not all of these pertain to the accident progression analysis. If nV_p variables are sampled in the accident progression analysis, then the pointer file contains nV_p entries which designate the quantities to be sampled. The sample file contains nLHS vectors, each of which consists of nV_p quantities.

For example, say the 55th quantity to be sampled is the containment failure pressure and the sample size is 200. The 55th pointer indicates the parameter used for the containment failure pressure. The evaluation of the LHS code[12] produces the 200 vectors that constitute the sample file; each of these vectors has a value for the containment failure pressure as the 55th entry. The LHS code selects the 200 values for the containment failure pressure so that the number of values in any pressure range is proportional to the probability density in that range; the probability distribution for the containment failure pressure was supplied by the structural expert panel. The LHS code also ensures that the 200 values chosen for the containment failure pressure are placed in the observations so that there are no unwanted correlations with other variables. When EVNTRE evaluates the APET in the sampling mode, for the first evaluation, the 55th value in the first sample vector replaces the containment failure pressure parameter value in the tree input file. For the second evaluation, the 55th value in the second sample vector replaces the containment failure pressure parameter value,

and so on. Once the tree input, pointer, and sample files are prepared, EVNTRE will perform the nLHS evaluations in a single computer run.

C.5.2 Rebinning of the APBs and other Postprocessing

The accident progression bins are not passed directly on to the source term analysis, but are first processed by the postprocessor code PSTEVNT.[11] This processing step is known as "rebinning." It often happens that the bins produced by EVNTRE do not exactly match those expected by XSOR, and PSTEVNT is used to eliminate the extra information or combine attributes. Obviously, PSTEVNT cannot supply information that is lacking in the original binning by EVNTRE. The original binning may contain more information than required for the initial conditions for the source term analysis because the analyst wished to examine certain features of the accident progression analysis. For Surry for example, the analyst was interested in differentiating between paths in which the sprays never operated and paths in which the sprays operated only in the very late period. It was determined that the operation of the sprays in the very late period had a negligible effect on the total release, so these two spray situations have separate attributes in the original binning but are combined into a single attribute in the rebinning by PSTEVNT.

PSTEVNT has other capabilities that were not used in the processing of the APBs generated in the production runs. All these capabilities are described in the user's manual.[11] For example, if the APETs for several PDS groups are run together, the bins for each PDS group will be separate, and a bin may appear more than once for a given observation. PSTEVNT may be used to produce a bin list in which each bin appears only once for each observation, with a probability that is the sum of the probabilities for each occurrence of the bin in the original bin output. PSTEVNT also has the capability to rebin or sort the original bins according to user-defined criteria and print various reports of the rebinned or sorted output. This ability eliminates the need to re-evaluate the tree in order to examine certain features of the accident progression analysis, and this feature was used extensively to examine the results of the analysis by isolating certain events or processes of interest. For example, to compare the reactor coolant system pressure at the onset of core damage and the pressure just before vessel failure, assuming that this information was preserved in the original binning, PSTEVNT could be used to rebin the original results, keeping only the binning information that pertains to RCS pressure and discarding the rest, thereby allowing the analyst to focus on the results of interest.

As used in the production runs for the accident progression and containment response analyses for NUREG-1150, PSTEVNT produces two files. The "rebinning result postprocessing report," known as the PST file, consists of rebinning information followed by rebinned bins and their frequencies on a by-observation basis. The "kept bins" file contains only a list of the rebinned bins, also on a by-observation basis. Following rebinning by PSTEVNT, two small codes are used to manipulate the bin information into the form required for subsequent steps in the complete analysis. These codes are MASTERK and XFRQ. XFRQ is the generic name for a separate code for each plant; SURFRQ for Surry, etc. The documentation of these codes is limited to the comments contained in the FORTRAN program.

MASTERK is used to combine the bins from the different PDS groups; it may be run in a "by-observation" mode or a "global" mode. The input to MASTERK is the kept bins file from PSTEVNT for each PDS group. The kept bins file for PDS Group 1 contains a list of bins for Observation 1, then a list of bins for Observation 2, and so on. There is a separate kept bins file for PDS Group 2 with similar information, a third file for PDS Group 3, etc. In the by-observation mode, MASTERK reads the files for all the PDS groups, and creates a file that contains a list of all the bins that appeared in any PDS kept bins file for Observation 1, then a list of all the bins that appeared in any PDS group kept bins file for Observation 2, and so on. Bins that appear in the kept bins file for more than one PDS group appear only once in the MASTERK output. This by-observation output file is used in the source term analysis and determines the bins for which source terms are computed for each observation. The global mode output of MASTERK is similar, but all observations are considered together; that is, there is just one list and it contains, only once, each bin identifier that appeared in the APET results for any PDS group and any observation. This global output file from MASTERK is one of the inputs to PARTITION (see Section 7.6).

The XFRQ codes are used to interleave PSTEVNT results to produce a file that has the results of all PDS groups in order by observation. XFRQ also obtains the PDS group frequencies from a TEMAC output file for each observation and includes that information in the XFRQ output file. That is, the output file from XFRQ first contains all the information for Observation 1: the frequency for PDS Group 1 followed by the APBs and APB probabilities for PDS Group 1; then similar information for PDS Group 2 for Observation 1, and so on. Following the information for the last PDS group for Observation 1, the file contains analogous information for Observation 2, and so on for all the observations in the sample. The output file from XFRQ is used as an input file for PARTITION and PRAMIS.

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FEDERAL REPUBLIC OF GERMANY

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Virginia Electric Power Co.
P. O. Box 26666
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Ronald Berryman [2]
Virginia Electric Power Co.
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Richmond, VA 23261

Robert C. Bertucio
NUS Corporation
1301 S. Central Ave., Suite 202
Kent, WA 98032

John H. Bickel
EG&G Idaho, Inc.
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Peter Bieniarz
Risk Management Association
2309 Dietz Farm Road, NW
Albuquerque, NM 87107

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James Blackburn
Illinois Dept. of Nuclear Safety
1035 Outer Park Drive
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Safety & Reliability Optimization
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Allan R. Brown
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SPAIN

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ITALY

James C. Carter, III
TENERA L.P.
Advantage Place
308 North Peters Road
Suite 280
Knoxville, TN 37922

John G. Cesare
SERI
Director Nuclear Licensing
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Jackson, MS 39211

S. Chakraborty
Radiation Protection Section
Div. De La Securite Des Inst. Nuc.
5303 Wurenlingen
SWITZERLAND

Sen-I Chang
Institute of Nuclear Energy
  Research
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Lungtan, 325
TAIWAN

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Yankee Atomic Electric Company
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BWR Assistant Director
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ITALY

Frank Coffman
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NUS Corporation
16835 W. Bernardo Drive
Suite 202
San Diego, CA 92127

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U.K. Atomic Energy Authority
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UNITED KINGDOM

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1500 Johnson Drive
Madison, WI 53706

E. R. Corran
Nuclear Technology Division
ANSTO Research Establishment
Lucas Heights Research Laboratories
Private Mail Bag 7
Menai, NSW 2234
AUSTRALIA

James Costello
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MS: NL/S-217A

George Crane
1570 E. Hobble Creek Dr.
Springville, Utah 84663

Mat Crawford
SERI
5360 I-55 North
Jackson, MS 39211

Garth Cummings
Lawrence Livermore Laboratory
L-91, Box 808
Livermore, CA 94526

Mark A. Cunningham
USNRC-RES/PRAB
MS: NLS-372

James J. Curry
7135 Salem Park Circle
Mechanicsburg, PA 17055

Peter Cybulskis
Battelle Columbus Division
505 King Avenue
Columbus, OH 53201

Peter R. Davis
PRD Consulting
1935 Savin Drive
Idaho Falls, ID 83401

Jose E. DeCarlos
Consejo de Seguridad Nuclear
Sor Angela de la Cruz 3, Pl. 8
28016 Madrid
SPAIN

M. Marc Decreton
Department Technologie
CEN/SCK
Boeretang 200
B-2400 Mol
BELGIUM

Richard S. Denning
Battelle Columbus Division
505 King Avenue
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Science Applications Int. Corp.
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CANADA

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ITALY

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Kernforschungszentrum
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D-7500 Karlsruhe
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John H. Flack
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Oak Ridge National Laboratory
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Pickard, Lowe & Garrick
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SWEDEN

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NUS Corporation
910 Clopper Road
Gaithersburg MD 20878

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FINLAND

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JBF Associates, Inc.
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John Garrick
Pickard, Lowe & Garrick, Inc.
2260 University Drive
Newport Beach, CA 92660

John Gaunt
British Embassy
3100 Massachusetts Avenue, NW
Washington, DC 20008

Jim Gieseke
Battelle Columbus Division
505 King Avenue
Columbus, OH 43201

Frank P. Gillespie
USNRC-NRR/PMAS
MS: 12G-18

Ted Ginsburg
Department of Nuclear Energy
Building 820
Brokhaven National Laboratory
Upton, NY 11973

James C. Glynn
USNRC-RES/PRAB
MS: NLS-372

P. Govaerts
Department de la Surete Nucleaire
Association Vincotte
Avenue du Roi 157
B-1060 Bruxelles
BELGIUM

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Building 820M
Brookhaven National Laboratory
Upton, NY 11973

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Postbus 1
NL-1755 Petten ZG
NETHERLANDS

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P. O. Box 3640
D-7500 Karlsruhe 1
FEDERAL REPUBLIC OF GERMANY

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Statens Karnkraftinspektion
P.O. Box 27106
S-10252 Stockholm
SWEDEN

Stephen Hanauer
Technical Analysis Corp.
6723 Whittier Avenue
Suite 202
McLean, VA 22101

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Husarenstrasse 30
Postfach 120629
D-5300 Bonn 1
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F. Heuser
Giesellschaft Fur Reaktorsicherheit
Forschungsgelande
D-8046 Garching
FEDERAL REPUBLIC OF GERMANY

E. F. Hicken
Giesellschaft Fur Reaktorsicherheit
Forschungsgelande
D-8046 Garching
FEDERAL REPUBLIC OF GERMANY

D. J. Higson
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P. O. Box 153
Rosebery, NSW 2018
AUSTRALIA

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University of California
A. Stevenson Program on
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Santa Cruz, CA 95064

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Hauptabteilung Sicherheit and
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Swiss Federal Institute for
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CH-5303 Wurenlingen
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Westinghouse Electric Corp.
Savanna River Site
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EG&G Idaho, Inc.
P. O. Box 1625
Idaho Falls, ID 83415

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Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831

Lars Hoegberg
Office of Regulation and Research
Swedish Nuclear Power Inspectorate
P.O. Box 27106
S-102 52 Stockholm
SWEDEN

Lars Hoeghort
IAEA A-1400
Wagranerstraase 5
P.O. Box 100
Vienna, 22
AUSTRIA

Edward Hofer
Giesellschaft Fur Reaktorsicherheit
Forschurgsgelande
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FEDERAL REPUBLIC OF GERMANY

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2260 University Drive
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W. Reed Johnson
Department of Nuclear Engineering
University of Virginia
Reactor Facility
Charlottesville, VA   22901

Jeffery Julius
NUS Corporation
1301 S. Central Ave., Suite 202
Kent, WA   98032

H. R. Jun
Korea Adv. Energy Research Inst.
P.O. Box 7, Daeduk Danju
Chungnam 300-31
KOREA

Peter Kafka
Gesèllschaft Fur Reaktorsicherheit
Forschungsgelande
D-8046 Garching
FEDERAL REPUBLIC OF GERMANY

Geoffrey D. Kaiser
Science Application Int. Corp.
1710 Goodridge Drive
McLean, VA   22102

William Kastenberg
UCLA
Boelter Hall, Room 5532
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Walter Kato
Brookhaven National Laboratory
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Upton, NY   11973

M. S. Kazimi
MIT, 24-219
Cambridge, MA   02139

Ralph L. Keeney
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Henry Kendall
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Frank King
Ontario Hydro
700 University Avenue
Bldg. H11 G5
Toronto
CANADA   M5G1X6

Oliver D. Kingsley, Jr.
Tennessee Valley Authority
1101 Market Street
GN-38A Lookout Place
Chattanooga, TN   37402

Stephen R. Kinnersly
Winfrith Atomic Energy
   Establishment
Reactor Systems Analysis Division
Dorset DT2 8DH
ENGLAND

Ryohel Kiyose
University of Tokyo
Dept. of Nuclear Engineering
7-3-1 Hongo Bunkyo
Tokyo 113
JAPAN

George Klopp
Commonwealth Edison Company
P.O. Box 767, Room 35W
Chicago, IL 60690

Klaus Koberlein
Gesellschaft Fur Reaktorsicherheit
Forschungsgelande
D-8046 Garching
FEDERAL REPUBLIC OF GERMANY

E. Kohn
Atomic Energy Canada Ltd.
Candu Operations
Mississauga
Ontario, L5K 1B2
CANADA

Alan M. Kolaczkowski
Science Applications International
  Corporation
2901 Air Park Road SE
Albuquerque, NM 87106

S. Kondo
Department of Nuclear Engineering
Facility of Engineering
University of Tokyo
3-1, Hongo 7, Bunkyo-ku
Tokyo
JAPAN

Thomas Kress
Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831

W. Kroger
Institut fur Nukleare
  Sicherheitsforschung
Kernforschungsanlage Julich GmbH
Postfach 1913
D-5170 Julich 1
FEDERAL REPUBLIC OF GERMANY

Greg Krueger [3]
Philadelphia Electric Co.
2301 Market St.
Philadelphia, PA 19101

Bernhard Kuczera
Kernforschungzentrum Karlsruhe
LWR Safety Project Group (PRS)
P. O. Box 3640
D-7500 Karlsruhe 1
FEDERAL REPUBLIC OF GERMANY

Jeffrey L. LaChance
Science Applications International
  Corporation
2901 Air Park Road SE
Albuquerque, NM 87106

H. Larsen
Riso National Laboratory
Postbox 49
DK-4000 Roskilde
DENMARK

Wang L. Lau
Tennessee Valley Authority
400 West Summit Hill Avenue
Knoxville, TN 37902

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Kent, WA 98031

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Y. H. (Ben) Liu
Department of Mechanical
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University of Minnesota
Minneapolis, MN 55455

Bo Liwnang
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Swedish Nuclear Power Inspectorate
P.O. Box 27106
S-102 52 Stockholm
SWEDEN

J. P. Longworth
Central Electric Generating Board
Berkeley Gloucester
GL13 9PB
UNITED KINGDOM

William J. Luckas
Brookhaven National Laboratory
Building 130
Utpon, NY 11973

Hans Ludewig
Brookhaven National Laboratory
Building 130
Upton, NY 11973

Robert J. Lutz, Jr.
Westinghouse Electric Corporation
Monroeville Energy Center
EC-E-371, P. O. Box 355
Pittsburgh, PA 15230-0355

Phillip E. MacDonald
EG&G Idaho, 'Inc., Inc.
P. O. Box 1625
Idaho Falls, ID 83415

Jim Mackenzie
World Resources Institute
1735 New York Ave. NW
Washington, DC 20006

Richard D. Fowler
Idaho Nat. Engineering Laboratory
P. O. Box 1625
Idaho Falls, ID 83415

A. P. Malinauskas
Oak Ridge National Laboratory
P. O. Box Y
Oak Ridge, TN 37831

Giuseppe Mancini
Commission European Comm.
CEC-JRC Eraton
Ispra Varese
ITALY

Lasse Mattila
Technical Research Centre of
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Lonnrotinkatu 37, P. O. Box 169
FINLAND

Joseph A. Murphy
USNRC-RES/DSR
MS: NLS-007

Kenneth G. Murphy, Jr.
US Department of Energy
19901 Germantown Rd.
Germantown, MD   20545

Robert L. Palla, Jr.
USNRC-NRR/PRAB
MS: 10 E4

Gareth Parry
NUS Corporation
910 Clopper Rd.
Gaithersburg, MD   20878

G. Petrangeli
ENEA Nuclear Energy ALT Disp
Via V. Brancati, 48
00144 Rome
ITALY

Ing. Jose Antonio Becerra Perez
Comision Nacional De Seguridad
  Nuclear Y Salvaguardias
Insurgentes Sur 1806
01030 Mexico, D. F.
MEXICO

William T. Pratt
Brookhaven National Laboratory
Building 130
Upton, NY 11973

William Raisin
NUMARC
1726 M. St. NW
Suite 904
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USNRC-NRR/PRAB
MS: 10A-2

Takashi Sato, Deputy Manager
Nuclear Safety Engineering Section
Reactor Design Engineering Dept.
Nuclear Energy Group, Toshiba Corp.
Isogo Engineering Center
8, Shinsugita-cho, Isogo-ku,
Yokohama 235, JAPAN

Martin Sattison
Idaho National Engineering Lab.
P. O. Box 1625
Idaho Falls, ID   83415

Louis M. Shotkin
USNRC-RES/RPSB
MS: NLN-353

Desmond Stack
Los Alamos National Laboratory
Group Q-6, Mail Stop K556
Los Alamos, NM   87545

T. G. Theofanous
University of California, S. B.
Department of Chemical and Nuclear
  Engineering
Santa Barbara, CA   93106

Distribution

Harold VanderMolen [10]
USNRC-RES/PRAB
MS: NLS-372

Magiel F. Versteeg
Ministry of Social Affairs and
Employment
P.O. Box 90804
2509 LV Den Haag
THE NETHERLANDS

Edward Warman
Stone & Webster Engineering Corp.
P.O. Box 2325
Boston, MA 02107

Wolfgang Werner
Gesellschaft Fur Reaktorsicherheit
Forschungsgelande
D-8046 Garching
FEDERAL REPUBLIC OF GERMANY

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E. D. Gorham, R. J. Breeding, J. C. Helton[1], T. D. Brown, W. B. Murfin[2], F. T. Harper, S. C. Hora[3]

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Sandia National Laboratories
Albuquerque, NM 87185-5800

[1]Arizona State University, Tempe, AZ 85287
[2]Technadyne Engineering Consultants, Inc., Albuquerque, NM, 87112
[3]University of Hawaii, Hilo, HI 96720-4091

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Division of Safety Issue Resolution
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11. ABSTRACT *(200 words or less)*

NUREG-1150 examines the risk to the public from five nuclear power plants. The NUREG-1150 plant studies are Level III probabilistic risk assessments (PRAs) and, as such, they consist of four analysis components: accident frequency analysis, accident progression analysis, and source term analysis, and consequence analysis. This volume summarizes the methods utilized in performing the last three components and the assembly of these analyses into an overall risk assessment. The NUREG-1150 analysis approach is based on the following ideas: (1) general and relatively fast-running models for the individual analysis components, (3) use of Monte Carlo techniques together with an efficient sampling procedure to propagate uncertainties, (4) use of expert panels to develop distributions for important phenomenological issues, and (5) automation of the overall analysis. Many features of the new analysis procedures were adopted to facilitate a comprehensive treatment of uncertainty in the complete risk analysis. Uncertainties in the accident frequency, accident progression and source term analyses were included in the overall uncertainty assessment. The uncertainties in the consequence analysis were not included in this assessment. A large effort was devoted to the development of procedures for obtaining expert opinion and the execution of the development of procedures for obtaining expert opinion and the execution of these procedures to quantify parameters and phenomena for which there is large uncertainty and divergent opinions in the reactor safety community.

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