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Evaluation of Severe Accident Risks: Quantification of Major Input Parameters

Experts' Determination of Structural Response Issues

Prepared by
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Sandia National Laboratories
Operated by
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R. J. Breeding, F. T. Harper, T. D. Brown, J. J. Gregory,
A. C. Payne, E. D. Gorham, W. Murfin[1], C. N. Amos[2]

Sandia National Laboratories
Albuquerque, NM 87185-5800

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[1]Technadyne Engineering Consultants, Inc., Albuquerque, NM
[2]Science Applications International Corporation, Albuquerque, NM

ABSTRACT

This report records part of the vast amount of information received during the expert judgment elicitation process that took place in support of the NUREG-1150 effort sponsored by the U.S. Nuclear Regulatory Commission. The results of the Structural Response Expert Panel Elicitation are presented in this part of Volume 2 of NUREG/CR-4551. The Containment Loads Expert Panel considered eight issues:

1. Static failure pressure and mode at Zion;
2. Static failure pressure and mode at Surry;
3. Static failure pressure and mode at Peach Bottom;
4. Reactor Building bypass at Peach Bottom;
5. Static failure pressure and mode at Sequoyah;
6. Ice condenser failure due to detonations at Sequoyah;
7. Drywell and wetwell failure due to detonations at Grand Gulf;
8. Pedestal failure due to erosion at Grand Gulf.

The report begins with a brief discussion of the methods used to elicit the information from the experts. The information for each issue is then presented in five sections: (1) a brief definition of the issue, (2) a brief summary of the technical rationale supporting the distributions developed by each of the experts, (3) a brief description of the operations that the project staff performed on the raw elicitation results in order to aggregate the distributions, (4) the aggregated distributions, and (5) the individual expert elicitation summaries. The individual expert elicitation summaries were written soon after the elicitation and were sent to the experts for review. They represent the raw results as received directly from the experts.

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Issue 4

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FOREWORD

This is one of many documents that constitute the technical basis for the NUREG-1150 document produced by the NRC Office of Nuclear Regulatory Research. This document's purpose is to present the results of the Structural Response Expert Panel. The document consists of the distributions and associated technical rationale provided by the expert panels for the phenomenological questions posed by the NUREG-1150 analysts.

Figure 1 identifies all the documents that present the results of the accident progression analysis, the source term analysis, the consequence analysis, and the overall risk integration. Three interfacing programs performed this work: the Accident Sequence Evaluation Program (ASEP), the Severe Accident Risk Reduction Program (SARRP), and the PRA Phenomenology and Risk Uncertainty Evaluation Program (PRUEP). Table 1 is a list of all of the original primary documentation (published in 1987) and the corresponding revised documentation that supports the current version of NUREG-1150.

The current NUREG/CR-4551 covers the analysis included in the original NUREG/CR-4551 and NUREG/CR-4700. The accident progression event trees originally documented in NUREG/CR-4700 are now documented in the appendices of Volumes 3 to 7 of NUREG/CR-4551.

Originally, NUREG/CR-4550 was published without the designation "Draft for Comment." Thus, the final 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"; so, in its final form, no Revision 1 designator is required to distinguish it from the previous documentation.

There are several other reports published that are closely related to NUREG/CR-4551:

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

NUREG/CR-5360, SAND89-0943, H.-N. Jow, W. B. Murfin, and J. D. Johnson, "XSOR Codes User's Manual," Sandia National Laboratories, Albuquerque, NM, 1989.

NUREG/CR-4624, BMI-2139, R. S. Denning et al., "Radionuclide Release Calculations for Selected Severe Accident Scenarios," Volumes I-V, Battelle's 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, 1989.

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, 1989.

NUREG/CR-5382, SAND88-2695, J. C. Helton et al., "Incorporation of Consequence Analysis Results into the NUREG-1150 Probabilistic Risk Assessments," Sandia National Laboratories, Albuquerque, NM, 1989.

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

NUREG/CR-5262, SAND88-3093, R. L. Iman, J. D. Johnson, and J. C. Helton, "PRAMIS: Probabilistic Risk Assessment Model Integration System User's Guide," Sandia National Laboratories, Albuquerque, NM, May 1990.

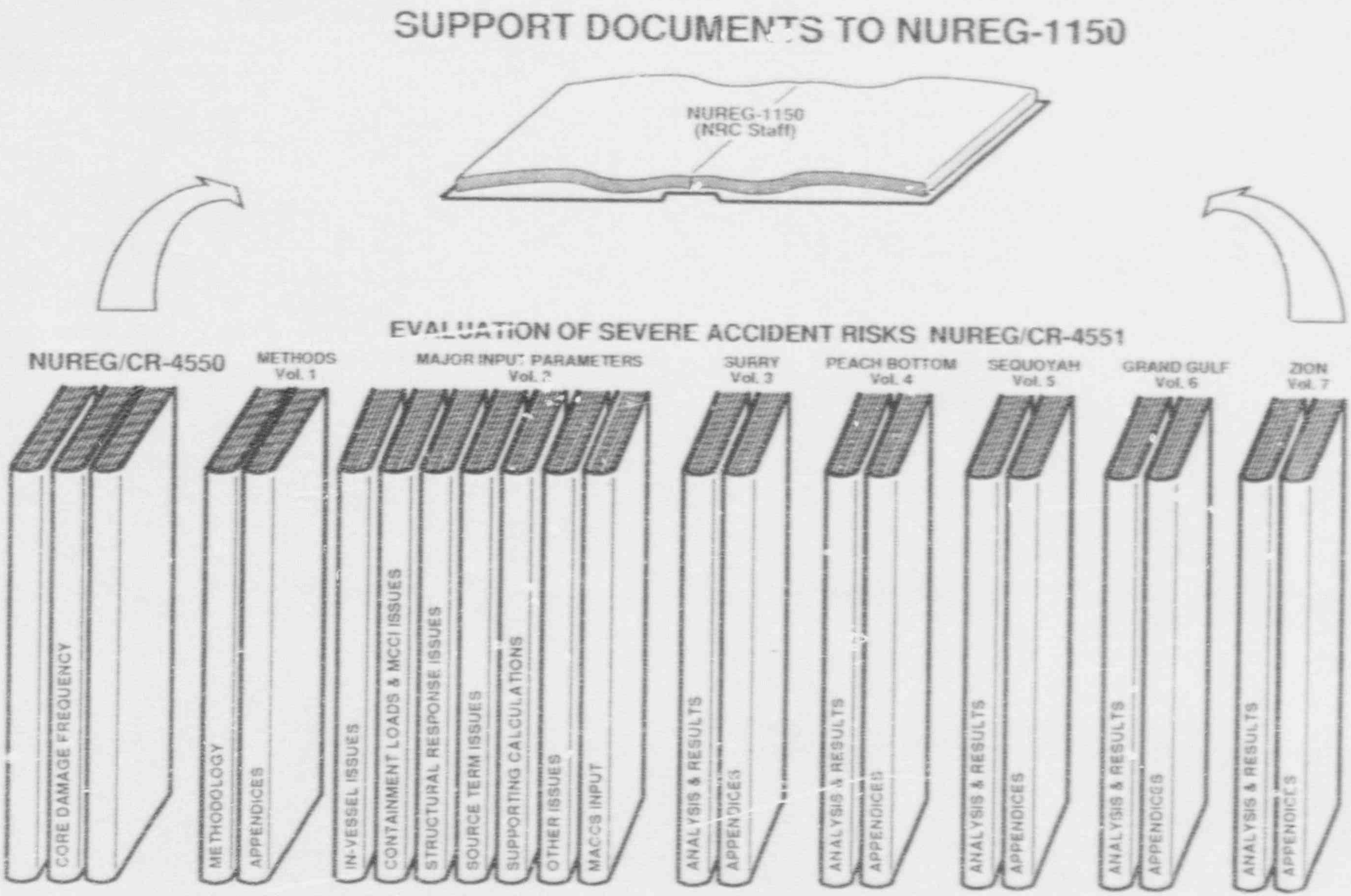

Figure 1. Back-End Documentation for NUREG-1150.

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. 1 Methodology	Vol. 1 Surry Unit 1	Vol. 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 Part 1, Methodology; Part 2, Appendices
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

ACRONYMS AND INITIALISMS

ADS	automatic depressurization system
AICC	adiabatic isochoric complete combustion
AIChE	American Institute of Chemical Engineers
ANL	Argonne National Laboratory
ANOVA	analysis of variance
ANS	American Nuclear Society
APET	accident progression event tree
ASEP	Accident Sequence Evaluation Program
ASME	American Society of Mechanical Engineers
ATWS	anticipated transient without scram
BNL	Brookhaven National Laboratory
BPNL	Battelle Pacific Northwest Laboratory
BWR	boiling water reactor
CCI	core-concrete interaction
CDF	cumulative distribution function
CL	containment load
CR	catastrophic rupture
CRD	control rod drive
DBA	design basis accident
DCH	direct containment heating
DDT	deflagration-to-detonation transition
DF	decontamination factor
DOE	Department of Energy
EPRI	Electric Power Research Institute
FCI	fuel-coolant interaction
FAI	Fauske and Associates, Inc.
FSAR	final safety analysis report
HPME	high pressure melt ejection
IC	ice condenser
IDCOR	Industry Degraded Core Rulemaking
INEL	Idaho National Engineering Laboratory
KFK	Kernforschungszenitum, Karlsruhe
LOCA	loss-of-coolant accident
LMFBR	liquid-metal fast breeder reactor
LMR	liquid-metal reactor
LSD	least significant difference
LWR	light water reactor
MAAP	Modular Accident Analysis Program
MCCI	molten core-coolant interactions
NRC	Nuclear Regulatory Commission

ORNL Oak Ridge National Laboratory

PORV power-operated relief valve
PRA probabilistic risk analysis
PWR pressurized water reactor

RCP reactor coolant pump
RCS reactor coolant system
RPV reactor pressure vessel
RF release fraction
RMA Risk Management Associates

SAARP severe accident risk reduction program
SAIC Science Applications International Corporation
S&L Sargent & Lundy
S&W Stone and Webster
SGTR steam generator tube rupture
SLC standby liquid control
SNL Sandia National Laboratories
SRV safety relief valve

TVA Tennessee Valley Authority

UHI upper head injection
USC University of Southern California

UCHB unconditional hydrogen burn
UP upper plenum

1. INTRODUCTION

The United States Nuclear Regulatory Commission (NRC) has prepared NUREG-1150[1] to examine the risk of accidents in a selected group of nuclear power plants. The three main objectives of NUREG-1150 are given below.

1. Prepare a current assessment of the severe accident risks of five nuclear power plants that will:

   - Provide a "snapshot" of risks reflecting plant design and operational characteristics, related failure data, and severe accident phenomenological information extant in March 1988;
   - Update the estimates of NRC's 1975 risk assessment, the Reactor Safety Study;[2]
   - Include quantitative estimates of risk uncertainty, in response to a principal criticism of the Reactor Safety Study; and
   - Identify plant-specific risk vulnerabilities, in context of the NRC's individual plant examination process.

2. Summarize the perspectives gained in performing these risk analyses, with respect to:

   - Issues significant to severe accident frequencies, consequences, and risks;
   - Uncertainties for which the risk is significant and which may merit further research;
   - Comparisons with NRC's safety goals;
   - The potential benefits of a severe accident management program in reducing risk; and
   - The potential benefit of other plant modifications in reducing risk.

3. Provide a set of methods for the prioritization of potential safety issues and related research.

In support of NUREG-1150 and as part of the Accident Sequence Evaluation Program (ASEP) and the Severe Accident Risk Reduction Program (SARRP), Sandia National Laboratories (SNL) has directed the production of Level 3 probabilistic risk assessments (PRAs) for the Surry, Sequoyah, Peach Bottom, and Grand Gulf nuclear power plants. (Level 1 PRAs contain accident sequence analyses developed to the point of core damage; Level 2 PRAs include Level 1 and accident progression analyses; and Level 3 PRAs include Level 1, Level 2, and consequence analyses.) A PRA for the fifth NUREG-1150 plant, Zion, has been prepared by EG&G Idaho, Inc., of the Idaho National Engineering Laboratory (INEL) (Level 1) and Brookhaven National Laboratory (BNL) (Levels 2 and 3). Two of these analyses (Surry and Peach Bottom) include external events.

Expert judgment elicitation is an integral part of the methods used to produce the PRAs in support of NUREG-1150. Expert judgment is used where applicable experimental data or complete analyses are inadequate. Such situations are common in analysis of rare events and complicated severe accident phenomena. The purpose of this report is to provide the results and technical rationale obtained from the Structural Response Expert Panel. The expert judgment methodology is presented in detail in NUREG/CR-4551 Volume 1.

Expert judgments are expressions of opinion, based on knowledge and experience, that experts make in responding to technical problems. Specifically, the judgments represent the expert's state of knowledge at the time of response to the technical question. Expert judgment is not restricted to the experts' answer but includes the experts' mental processes (definitions, assumptions, and algorithms) for arriving at answers.

Expert judgment is necessarily used in all technical fields. Because these judgments are often implicit, they are sometimes not acknowledged as being expert judgments. For example, expert judgment is frequently used implicitly, even unconsciously, when researchers make decisions about defining problems, establishing boundary conditions, or screening data. By contrast, expert judgment is obtained explicitly, through formal processes.

Risk assessment frequently needs explicit expert judgment as a source of data, particularly if one or more of the following situations exist:

1. No other data (analytical or experimental) for predicting the outcome of phenomena are available;

2. High variability characterizes the data;

3. Experts question the applicability of the data;

4. Existing data need to be supplemented, interpreted, or incorporated with model or code calculations;

5. Analysts need to determine the state of knowledge about what is currently known, what is not known, and what is worth learning.

The issue selection process consisted of accumulating an extensive list of potential issues by plant or across plants and then evaluating the significance of each issue. Expert panel members participated in the issue selection by reviewing the issues selected and rejected for the expert judgment process and recommended the addition, deletion, or modification of issues from the initial list.

Eight structural response issues were considered important enough to be the subject of a formal expert judgment elicitation. Table 1-1 lists these issues.

Section 2 of this report briefly outlines the expert selection process and gives a short biographical sketch of each expert. Section 3 describes the fundamental expert judgment elicitation methodology. Section 4 lists the meetings held for the Structural Response Expert Panel and the people who gave presentations at the meetings. Section 5 constitutes the bulk of this report and contains a description of each issue considered, a summary of the technical rationale applied by the experts to the issue, a description of the method used to aggregate the expert's distributions, the aggregated distributions, and written accounts of each individual response to the question. The individual expert's narrative includes the distributions and the detailed rationale behind the distributions. Each account was written by the substantive expert who assisted with the elicitation. In all cases, the experts were given ample opportunity to review these written accounts and approve them. In a few cases, the experts did not respond and were informed that their lack of response would be assumed to be tacit approval of the write-up.

Table 1-1
Structural Response Issues Considered for
Expert Judgment Elicitation

Issue No.	Title	Applicable Plants
1	Static failure pressure and mode at Zion	Zion
2	Static failure pressure and mode at Surry	Surry
3	Static failure pressure and mode at Peach Bottom	Peach Bottom
4	Reactor Building bypass at Peach Bottom	Peach Bottom
5	Static failure pressure and mode at Sequoyah	Sequoyah
6	Ice condenser failure due to detonations at Sequoyah	Sequoyah
7	Drywell and wetwell failure due to detonations at Grand Gulf	Grand Gulf
8	Pedestal failure due to erosion at Grand Gulf	Grand Gulf

REFERENCES

1. U.S. Nuclear Regulatory Commission, "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants," Vol. 1, Office of Nuclear Regulatory Research, Washington, D.C., NUREG-1150, June 1989.

2. U.S. Nuclear Regulatory Commission, "Reactor Safety Study--An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," U.S. Nuclear Regulatory Commission, WASH-1400 (NUREG-75/014), Washington D.C., 1975.

2. EXPERT CREDENTIALS

The objective for selecting the panel members was to obtain experts with as much expertise as possible in the field of Nuclear Power Plant Containment/Reactor Building Structural Response. The project attempted to include a wide diversity of expertise that encouraged alternative points of view. The selection of experts should preclude stakeholders in the findings of NUREG-1150 from participating as members of the expert panel. This led to several criteria in selecting the experts:

1. Experts should have to demonstrate experience by authoring publications, hands-on experience, and consulting or managing research in the areas related to the issues;

2. Experts should have to represent a wide variety of experience as is obtained in universities, consulting firms, laboratories, nuclear utilities, or government agencies;

3. The experts should have to represent as wide a perspective of the issues as possible;

4. The experts should be willing to be elicited under the methodology to be used.

To ensure proper representation, letters were sent to many organizations requesting nominations for experts to serve on the in-vessel, containment loads, molten core/containment interaction, structural response, and source term panels. Some of the organizations that received these letters are listed below:

Atomic Energy of Canada LTD.
Battelle Columbus Division
Bechtel Western Power Company
Brookhaven National Laboratory
Commonwealth Edison
Electric Power Research Institute
General Electric
Idaho National Engineering Laboratory (EG&G Idaho, Inc.)
Illinois Department of Nuclear Safety
International Technology Corporation
MHB Technical Associates
New York Power Authority
NUMARC
Oak Ridge National Laboratory
Philadelphia Electric Co.
Sandia National Laboratories
Stone and Webster Engineering Corporation
Systems Energy Resources, Inc.
Tennessee Valley Authority
U.S. Nuclear Regulatory Commission
Virginia Electric Power Co.
Westinghouse Electric Corp.

It was impossible to satisfy each criterion entirely for every expert/issue combination. Nevertheless, we were pleased with the high quality and objectivity of the experts. The experts chosen for the structural response issues were:

David Clauss	Sandia National Laboratories
Charles Miller	City College of New York
Kam Mokhtarian	Chicago Bridge & Iron Co. Na-Con, Inc.
Joe Rashid	ANATECH Research Corp.
Subir Sen	Bechtel Power Corp.
Richard Toland	United Engineers and Construction
Walt von Riesemann	Sandia National Laboratories
Adolph Walser	Sargent & Lundy
Joe R. Weatherby	Sandia National Laboratories
Don Wesley	IMPELL

Brief biographical sketchs of the experts are presented below.

Structural Response Expert Panel

DAVID CLAUSS

David Clauss joined Sandia National Laboratories in 1980. He is a project leader on a containment integrity program for NRC that involves determining structural strength of concrete and steel containment models when subjected to stress from seismic, pressure, and temperature overloading. When conducting tests, he specified test objectives and environment, planned instrumentation, calculated structural response, and interpreted results. Previously, he performed both heat transfer and structural analysis in support of design efforts for a post-accident heat removal experiment. He also investigated structural problems arising during fabrication and operation of solar panels and conducted thermal stress analysis for combustor tubes for a downhole steam generator used in enhanced oil recovery. He received a B.S. (1979) and a M.S. (1980) in Mechanical Engineering from the University of Michigan.

CHARLES MILLER
(No biographical sketch provided.)

KAM MOKHTARIAN

Kam Mokhtarian is a Senior Engineer with Chicago Bridge & Iron Company. He holds a Masters Degree in Structural Engineering from Northwestern University. His background is mostly in the design and analysis areas of nuclear structures. He has served in a number of supervisory assignments related to design and analysis of containment vessels, reactor vessels, and other pressure vessels. He has served on a number of NRC's peer review groups, related to structural safety of containment vessels. He is the author of a number of papers related to design of shell structures. He is a member of the American Society of Mechanical Engineers' (ASME's) Boiler & Pressure Vessel Code Committee and has served on a number of projects with the Pressure Vessel Research Committee of the Welding Research Council.

JOE RASHID
(No biographical sketch provided.)

SUBIR SEN
(No biographical sketch provided.)

RICHARD TOLAND

Richard Toland is the Chief Structural Engineer of the Stearns Catalytic Division of United Engineers and Constructors (UE&C), Philadelphia, PA. He holds a Ph.D in Applied Mechanics from the University of Delaware. In the past 10 years at UE&C, he has worked primarily in support of the design development of nuclear power plants, including containment structures. Dr. Toland has performed special containment ultimate capability studies of the Indian Point 2 & 3, Seabrook and Brunswick 1 & 2 containment systems. he provided expert witness testimony before the Atomic Safety and Licensing Board in the reopened Indian Point hearings, and he has made presentations on containment capability before the NRC, the Advisory Committee on Reactor Safety and Brookhaven National Laboratory. Dr. Toland participated in the Industry Degraded Core Rulemaking (IDCOR) Task 10 on containment capability and more recently, UE&C's design and construction of the 1/6th scale reinforced concrete containment structure for the NRC and Sandia National Laboratories, a significant task in the NRC's support of containment capability research. He has also recently supported studies of containment concepts for DOE's proposed New Production Reactor (NPR). Before joining UE&C, Dr. Toland was a section leader at the Lawrence Livermore National Laboratory where he directed a program on long-term life characteristics of high performance pressure vessels and their reliability under sustained loads. He presently serves on technical committees for the American Concrete Institute, the American Society of Civil Engineers and the American Society for Testing and Materials.

WALTER A. VON RIESEMANN

Dr. von Riesemann joined Sandia National Laboratories in July 1960. Since 1977, he has been the Supervisor of the Containment Technology Division. He received an M.S. in Civil Engineering from the University of Illinois in 1959, and a Ph.D in Civil Engineering from Stanford University in 1968. As a Supervisor, he is involved in programs for the Nuclear Regulatory Commission (NRC), the Department of Energy (DOE), and the Electric Power Research Institute (EPRI) dealing with the safety of light water reactors (LWRs). In the past he has also directed programs on quantification testing of components and fire protection research. At present he is directing containment integrity programs for the NRC that involve structural strength of containments when subjected to static and dynamic internal overpressurization loads and to earthquake loads, and the behavior of penetrations including electrical penetrations when subjected to severe accident loads. These programs involve the testing of scale models and are a multi-year, multi-million dollar activity.

ADOLPH WALSER

Adolf Walser is an associate in the architect/engineering firm of Sargent & Lundy in Chicago. He received his diploma in civil engineering from the Federeal Technical University (ETH) in Zurich in 1949. He worked in Switzerland and other countries as a structural design engineer until 1958 when he moved to the United States. He became chief engineer and later manager of the Post-tensioning Deparcment at Joseph T. Ryerson & Son, Inc., in Chicago. In 1967 he joined Sargent & Lundy where he worked as a structural design engineer, later as supervisor of the special structures section and presently as Senior Structural Project Engineer primarily on nuclear power plants. His responsibilities include design and anlaysis and project engineering of structures such as containments, special structures and other parts of nuclear power plants. He is a Fellow of the American Concrete Institute and a member of the Technical Committee on concrete pressure components for nuclear service of ACI/ASME. He has authored or co-authored more than 25 papers on the subject of design, analysis, and construction of containments and other structures.

J. RANDALL WEATHERBY

J. Randall Weatherby is a Senior Member of Technical Staff at Sandia National Laboratories. He holds a PhD in Mechanical Engineering from Texas A&M University. Randall joined Sandia in February 1986. As a structural analyst, he has supported Sandia's programs in reactor safety. He participated in the analysis and testing of a 1:6-scale reinforced concrete containment structure for the NRC.

DON WESLEY
(No biographical sketch provided.)

3. METHODOLOGY

3.1 Introduction

This section contains a summary of the methodology used to elicit expert judgment from the expert panels. An in-depth discussion of the methodology is contained in Volume 1 of NUREG/CR-4551.

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 development of the 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 does it 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.

3.2 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[1,2] 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.

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, were discussed 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.

3.3 Selection of Issues

The NUREG-1150 program attempts to show the range and distribution of risk due to uncertainty in the inputs. Some of that uncertainty is phenomenological, some is stochastic, and some is because of limited background of data. There are an enormous number of input points, and all are uncertain to some extent. It was thus impossible to treat all questions and issues with the same degree of thoroughness. The criteria used to select issues for detailed uncertainty analysis were:

- <u>High impact on risk</u>. If an issue 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.

- Interest within the reactor safety community. Some issues were thought not to be major determinants of uncertainty in risk, but had nevertheless been the subject of intense investigation and debate. The reason for including these issues in the analysis was to confirm this opinion.

- To improve on the treatment in Draft NUREG-1150. Some issues had not appeared to be important in the draft version; however, it was recognized that the treatment there was less than optimum. Such issues were included to determine whether an improved treatment would change those insights.

- The issue was uncertain. Even if an issue is important for the magnitude of risk, if the outcome is certain there is no impact on the uncertainty in risk.

Issues meeting any of these criteria were listed by the NUREG-1150 staff. The preliminary list of issues was presented to a panel of experts, along with reasons for their inclusion. A list of other 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 for quantification of the 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: uncertain issues affecting the sequence frequency calculation, uncertain issues affecting the response of the containment and its systems, and uncertain issues affecting the radiological source term. There were more issues affecting containment than for the other classes, and there was a further breakdown into issues related to the in-vessel phenomenology, containment loads, structural response, and molten core-concrete interactions. Tables 3-1 through 3-5 show the issues presented to the containment and radiological source term expert panels, along with the reasons for including the issue.

Table 3-1
Issues Presented to the In-Vessel Panel

Issue No.	Title	Reason for Inclusion
1	Temperature-induced pressurized water reactor (PWR)	Large hot leg failure could preclude direct containment heating; depressurizes RCS and precludes steam generated tube rupture (SGTR)
2	Temperature-induced PWR SGTR	SGTR gives direct path to environment, with large release of radionuclides
3	In-vessel hydrogen production in boiling water reactors (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 3-2
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 3-3
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 wet-well 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 3-4
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 3-5
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 deconta-mination factor (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	Core-concrete contain-ment (CCI) release	If in-vessel release is low, CCI release could be high; uncertain issue
5	Release of RCS and CCI species from contain-ment	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

3.4 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. A brief summary of their credentials was presented in Section 2.

3.5 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. The trainer for the Structural Response Expert Panel was Steve Hora, University of Hawaii, Hilo.

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 probability elicitation. The expertise possessed by the scientists and engineers on the panels is called substantive expertise and thus they are called substantive experts. Expertise about probability elicitation is called normative expertise and the participants in the expert opinion process schooled in probability assessment are known as normative experts. Both substantive expertise (knowledge of the problem domain being studied) and normative expertise (knowledge of techniques for encoding beliefs into probability distributions) are required for a successful expert opinion process.

During probability training, experts are exposed to various techniques for probability elicitation and the difficulties that accompany probability elicitation. Once trained, substantive experts are better able to express their knowledge in the form of probabilities and the resulting elicitations will be of a better quality. The resulting assessments are better calibrated in the sense that they accurately reflect the expert's knowledge and uncertainty. 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 probability distributions.

Another benefit of training is that the time spent by the experts preparing for the issues is used more effectively because the experts can direct their analyses to the questions that must be addressed in the elicitation sessions. Further, the elicitation sessions run smoothly since the normative and substantive experts are working with the same definitions and the same understanding of the desired product.

3.5.1 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 for the probabilities of various types of quantities and events or phenomena, the psychological aspects of probability assessments, 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 formalized 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. At appropriate points in the training, the experts were asked to make assessments using the methods under discussion. Using practice assessments develops confidence and ensures that the substantive experts understand the tasks that they will be required to perform. In order to make the training more interesting and more relevant, examples were used that reflected nuclear power risk issues.

Since many of the assessments would require the development of a probability distribution for a continuous quantity, the experts were given training in both the direct assessment techniques (assessing probabilities of given intervals of values) and bisection techniques (assessing values of the variable having given cumulative probabilities) for continuous variables. Later, in the elicitation sessions, these techniques would be used interchangeably by the normative experts.

A discussion of stochastic and parametric uncertainties and how they are differentiated in an uncertainty analysis was also provided. The concept of calibration of experts and calibration functions was also introduced. However, mathematical calibration of experts was not attempted in the NUREG-1150 expert opinion process.

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 that expressed probability distribution expresses 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.

At the end of the training session, the participants were given an assessment training quiz containing 16 assessment tasks using the direct and bisection methods of assessment. The participants were asked to complete the training quiz during that evening and return the next morning to discuss the results. The purpose of the training exercise was two-fold: to give the substantive experts experience with the elicitation instruments and to provide feedback on the quality of the individual's assessments. As expected, most participants found that their assessed distributions expressed overconfidence. Once aware of this tendency, it is easier for the substantive experts to correct for this bias.

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. The net result is that the resulting probability distribution is a better expression of the expert's knowledge than if the expert had been asked to make an assessment of the initial issue without the aid of a decomposition.

Training in decomposition was conducted by presenting examples of decompositions that had been developed for the NUREG-1150 study. Several types of decompositions were shown and the process of recombining the assessments was discussed. Comments from the participants indicated that the use of problems from the nuclear safety area enhanced the value of the decomposition training.

3.6 Presentation of Issues

During the second part of 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.

Each presentation included a suggested decomposition of the problem. Problem decomposition has been used in the NUREG-1150 expert judgment process as a mechanism to improve the quality of the subjective assessments. Problem decomposition improves the quality of assessments by structuring the analysis so that the expert is required to make a series of simpler assessments rather than one complex assessment. Experimental studies[3,4] have shown that decomposition often improves the accuracy of assessments. Improvement occurs because the experts are responding to questions that are less difficult to answer. The experts must state their reasoning explicitly by being more introspective about their assumptions of the analysis and thus consider alternatives that they might otherwise ignore. Some improvement may be due to cancellation of errors which occurs when errors of underestimation are offset by comparable errors of overestimation. Decomposition also provides a form of self documentation since the expert's thought process is made explicit in the decomposition.

Plant analysts usually presented the suggested decompositions without the 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 analyst 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.

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.

3.8 Elicitation

The discussion of each issue was followed by elicitation meetings between the experts and a team composed of one normative analyst and one substantive analyst. Documentation of the experts' assumptions and reasoning was produced during the elicitation meetings. Normally, each meeting consisted of three participants (one panel member, a normative expert, and a substantive expert) and lasted about two hours. 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 the decomposition and assessments of the problems. The experts were required to explain their thinking to the assessment team of one normative and one substantive expert. During the discussion of the elicitation process, the expert being elicited was questioned about stated beliefs and asked to reflect on, and explain the reasoning behind, the values that he or she had provided. In many cases, the resulting decompositions and probability distributions differed somewhat from the initial assessments.

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. Normative experts have the ability to draw from the experts the important details being elicited. Their talent for becoming involved in the technical aspects of issues, which are not their basic area of expertise, is a crucial factor in facilitating the experts' abilities to develop logically consistent assessments. Such individuals are necessary in any expert judgment elicitation process.

The role of the substantive expert was to assist the expert by answering questions related to the issue and to ensure that technical reasoning was complete and to the point. He also served as a technical advisor to the normative expert to assist him in questioning the expert in a direction consistent with the technical needs and constraints of the plant analysis teams.

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.

Documentation of the elicitations is provided in Section 5 of this report. Note that while the experts participating for each issue are identified, the individual assessments are kept anonymous, and the experts are identified as Experts A, B, C, etc.

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 idiosyncratic case structures. On some issues, the experts expanded the case structure beyond what was tractable in the accident progression event trees (Section 4) or the XSOR codes (Section 5). On some issues, experts gave their results in different forms.

For the purposes of aggregation, it was absolutely required that the case structure be small enough to fit into 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 cases were not significant compared to the differences between experts; that is, the large and complex case structure had little effect on the dependent variable. A mathematical procedure was then used to determine which of the cases could be safely combined.

If different experts used different cases, they were first encouraged to resolve their differences; if they failed to do so it was necessary to find some common ground. The cases common to all experts were of course retained. The remaining cases were inspected, and the most important ones were retained. If an expert did not have one of these cases, but did have a closely analogous case, the analog was used for the missing case. If the expert did not have a case closely related to the missing case, then the average of the case for all other experts was used for his missing case. It was recognized that this procedure would reduce the range of uncertainty, so the substitution was resorted to as little as possible. For some issues, missing data could be filled in by interpolation or ratios of existing cases.

If the experts produced different dependent variables, some analysis was required to put all the outputs into the same form. Whenever this was done the experts involved might find the final form of their data difficult to reconcile with what had been produced in the elicitation. Therefore, analytical alteration of results was resorted to as little as possible, and attempts were made to explain the reasons for and methods of analysis to the experts.

After each of the experts' distributions were 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.

3.10 Review

Following the recomposition of the assessments and the modification of the documentation accompanying each assessment, the written analyses of each issue were returned to each panel expert, normative expert, and substantive expert associated with the issue for review. This review process ensured that potential misunderstandings were identified and resolved and that the documentation, which is given in Section 5 of this report, correctly reflects the judgment of the experts involved.

3.11 Documentation

Clear, comprehensive documentation is crucial for ensuring that the expert opinion process is accepted as credible. There must be no question as to the openness and impartiality of the process. Users and reviewers of the results must be able to trace the development of aggregated assessments from the information presented to the experts to the rationale that motivates each expert to generate his particular assessments, and through the process of aggregating the individual assessments into a final result, including any manipulation of the assessments needed for aggregation. To this end, the issue discussions were recorded on video cassette. Such recording provides evidence of the exact conversations and presentations made before the panel. Written notes were taken by both the normative and substantive experts. Each expert was encouraged to personally document his rationale for his elicitation immediately at the end of the session. By far the most important documentation is each expert's in-depth discussion of his reasoning for his assessments. The discussion should contain the technical foundation of information (experience, issue presentation, existing data or analyses) from which the rationale for the assessment is derived.

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4. ELICITATION MEETINGS

The first two meetings (the elicitation training and the presentation and review of the technical issues) for the Structural Response Expert Panel were held from November 30 to December 2, 1987. Presentations to the Structural Response Expert Panel were made by the following people:

Nestor Ortiz, SNL
Steve Hora, University of Hawaii, Hilo
Frederick Harper, SNL
Eric haskin, SNL
Roger Breeding, SNL
Adolph Walser, Sargent & Lundy
Walt von Riesemann, SNL
Arthur Payne, SNL
Kam Mohktarian, CB&I
Morris Reich, BNL
Walt Murfin, Technadyne
David Clauss, SNL
Marty Sherman, SNL
Elaine Gorham, SNL
Subir Sen, Bechtel
Tom Brown, SNL

The elicitation meeting for the Structural Response Expert Panel was held from January 15 to 21, 1988.

Normative experts for Structural Response elicitation sessions were:

Ralph Keeney, USC
Detlof von Winterfeldt, USC
Richard John, USC.

5. ISSUE DESCRIPTIONS AND ELICITATION RESULTS

The results of the expert panel elicitations are presented in detail here. A brief description of each issue is given, the individual expert assessments and rationale for the assessments are discussed, and the aggregated results or resolutions for each issue are presented.

5.1 Issue 1. Containment Failure at Zion

Experts Consulted: Charles Miller, City College of New York; Adolph Walser, Sargent & Lundy; Joe R. Weatherby, Sandia National Laboratories.

Issue Description

What distribution characterizes the failure pressures for static loading of the Zion containment? What conditional probabilities describe the failure modes for each pressure?

The Zion containment is a prestressed, post-tensioned concrete cylinder with a shallow-domed roof. The foundation is a reinforced concrete slab. The containment is lined with welded 0.25-in. plate steel. The post-tensioning system is composed of 63 dome tendons, 216 vertical tendons, and 555 hoop tendons. The design pressure and temperature are 47 psig and 217°F. The free volume is about 26,000,000 ft^3.

Three pressure rise cases were described in the original definition of the issue:

1. Pressure Spike at Vessel Breach,
2. Late Deflagration, and
3. Late, Gradual Pressure Rise.

Typical rise times for cases 1 and 2 would be in the order of a few seconds. While very high atmospheric temperatures might be observed for a fraction of a minute in case 1, the bulk temperature of the steel liner which forms the pressure boundary is not expected to exceed 300 to 350°F for any of the cases.

The initial definition of a large hole or rupture was an opening larger than 1.0 ft^2, which resulted in depressurization in less than 2 h. A small hole or leak was anything smaller than 1.0 ft^2 which did not result in depressurization in less than about 2 h. A review of this matter showed that large dry containments would depressurize in 2 h for hole sizes on the order of 0.3 to 0.5 ft^2. Thus, a small hole or leak should have been on the order of 0.1 ft^2, and 1.0 ft^2 is definitely a large hole or rupture. The panel members were asked to reconsider the distributions they provided in light of this redefinition of the hole size. Some of them adjusted their distributions for this or for some other reason. The failure mode "Catastrophic Rupture" (CR) was added at the time of elicitation. The containment failure implied by this failure mode is complete failure of a substantial portion of the containment pressure boundary, with possible disruption of the piping systems that penetrate or are attached to the containment wall. No similar gross structural failure is implied by the "Rupture" failure mode.

Summary of Results

The three panel members considering this issue all agreed that the three cases could be considered together since the pressure rise times were slow enough that the effects were all static. It was pointed out to the experts that the development of a leak would not arrest the pressure rise for cases 1 and 2, but they did not choose to provide separate distributions for these two cases. However, some of the experts allowed for the possibility that the development of a leak would not arrest the pressure rise by providing rupture and CR probabilities for pressures greater than the pressure for which they thought the development of a leak was certain. The experts further agreed that there was no need to differentiate between cases on the basis of temperature. The temperatures described were all low enough that there was no appreciable structural effect, i.e., no significant changes in material properties. Two of the experts based their conclusions on an analysis of the mid-section of the cylindrical portion of the containment (hoop failure); the reinforcing and concrete details in the cylinder-basemat junction area were such that both of them ruled out the possibility of shear failure in that location. The third expert, however, considered that shear failure was of importance, and made his analysis accordingly.

Since the fission products are released aboveground for a hoop failure of the cylinder and belowground for a shear failure at the cylinder-basemat junction, source terms for the hoop and shear rupture mode will differ significantly. Thus, the modes need to be considered separately during the containment analysis. It was considered unnecessary though to introduce a fifth mode to distinguish shear failure by leak, since leak failure at vessel breach is not expected to be risk dominant. All forms of leak (hoop and shear failures) are binned together.

The joint probability (density) distributions of the three experts are given in Tables 1-1 through 1-3. Based on a hoop strain analysis, Expert A concluded that failure would probably occur between 120 psig and 145 psig. Half of his probability lies between 130 and 140 psig. The leak failure mode was judged more likely to occur at the lower pressures and rupture more likely at the higher pressures. Expert B's analysis led him to conclude that the failure would be a leak in the cylindrical portion of the containment or a leak or a rupture at the cylinder-basemat junction. He placed the bulk of his hoop failure probability around the pressure at which the tendons reach their ultimate strength, 136 psig. The highest probability of shear failure also lies in the 125 to 150 psig range. Expert C concluded that hoop failure was certain to occur between 128 and 137 psig, and that leaks and ruptures are much more likely than catastrophic ruptures. The initial failure will probably be a small liner tear, which will increase in length if development of a leak does not arrest the pressure rise.

Table 1-4 gives the aggregate distribution. Table 1-5 gives the probability (density) of failure and the joint probability for the four failure modes. The marginal probabilities of failure are 0.48 for leak, 0.18 for hoop rupture, 0.05 for shear rupture, and 0.29 for catastrophic rupture. The three experts's opinions were aggregated as explained in the next section. The median of the average distribution is about 133 psig, and most failures at this pressure result in a leak. The 5% and 95% failure pressures are 94 psig and 170 psig, respectively. Figure 1-1 below shows a plot of the aggregate cumulative probability distribution for failure pressure with the individual experts' distributions.

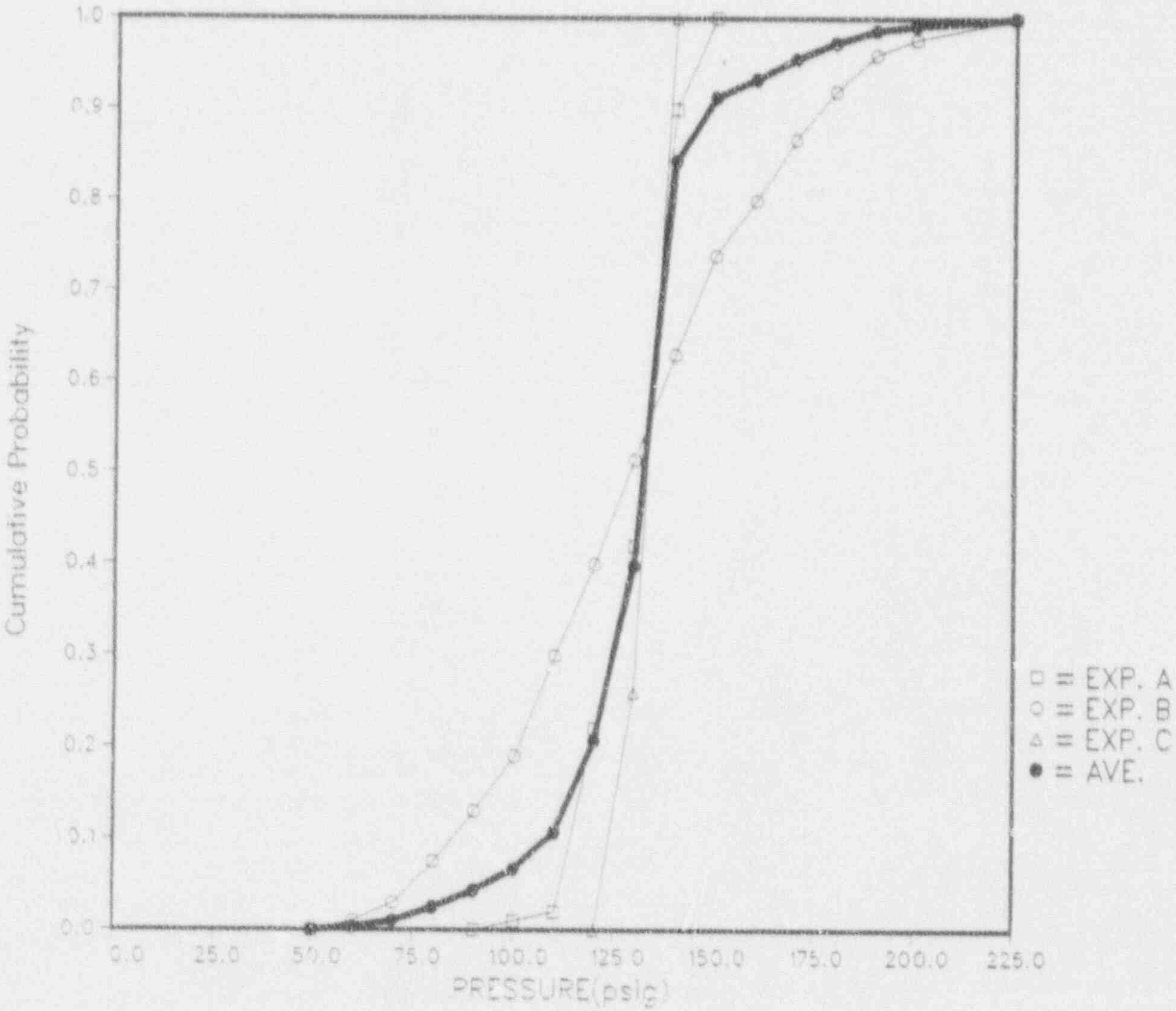

Figure 1-1. Zion Containment Failure Pressure.

Table 1-1
Expert A

Pressure (psig)	Cumululative Failure Probability	Conditional Probabilities for Failure Mode			
		Leak	Rupture (Hoop)	Rupture (Shear)	Catastrophic Rupture
50	0.000	1.000	0.000	0.000	0.000
60	0.000	1.000	0.000	0.000	0.000
70	0.000	1.000	0.000	0.000	0.000
80	0.000	1.000	0.000	0.000	0.000
90	0.000	1.000	0.000	0.000	0.000
100	0.010	1.000	0.000	0.000	0.000
110	0.020	1.000	0.000	0.000	0.00[illegible]
120	0.220	0.670	0.280	0.000	0.0[illegible]
130	0.420	0.460	0.380	0.000	0.160
140	0.900	0.130	0.340	0.000	0.530
150	1.000	0.000	0.000	0.000	1.000
160	1.000	0.000	0.000	0.000	1.000
170	1.000	0.000	0.000	0.000	1.000
180	1.000	0.000	0.000	0.000	1.000
190	1.000	0.000	0.000	0.000	1.000
200	1.000	0.000	0.000	0.000	1.000
225	1.000	0.000	0.000	0.000	1.000

Table 1-2
Expert B

Pressure (psig)	Cumululative Failure Probability	Conditional Probabilities for Failure Mode: Leak	Rupture (Hoop)	Rupture (Shear)	Catastrophic Rupture
50	0.000	1.000	0.000	0.000	0.000
60	0.010	0.980	0.000	0.020	0.000
70	0.030	0.960	0.000	0.040	0.000
80	0.075	0.946	0.000	0.054	0.000
90	0.130	0.938	0.000	0.062	0.000
100	0.190	0.930	0.000	0.070	0.000
110	0.300	0.920	0.000	0.080	0.000
120	0.400	0.910	0.000	0.090	0.000
130	0.515	0.880	0.000	0.120	0.000
140	0.630	0.840	0.000	0.160	0.000
150	0.740	0.790	0.000	0.210	0.000
160	0.800	0.750	0.000	0.250	0.000
170	0.867	0.680	0.000	0.320	0.000
180	0.920	0.630	0.000	0.370	0.000
190	0.960	0.590	0.000	0.410	0.000
200	0.977	0.550	0.000	0.450	0.000
225	1.000	0.500	0.000	0.500	0.000

Table 1-3
Expert C

Pressure (psig)	Cumululative Failure Probability	Conditional Probabilities for Failure Mode			
		Leak	Rupture (Hoop)	Rupture (Shear)	Catastrophic Rupture
50	0.000	1.000	0.000	0.000	0.000
60	0.000	1.000	0.000	0.000	0.000
70	0.000	1.000	0.000	0.000	0.000
80	0.000	1.000	0.000	0.000	0.000
90	0.000	1.000	0.000	0.000	0.000
100	0.000	1.000	0.000	0.000	0.000
110	0.000	1.000	0.000	0.000	0.000
120	0.000	1.000	0.000	0.000	0.000
130	0.260	0.970	0.030	0.000	0.000
140	1.000	0.060	0.300	0.000	0.640
150	1.000	0.000	0.000	0.000	1.000
160	1.000	0.000	0.000	0.000	1.000
170	1.000	0.000	0.000	0.000	1.000
180	1.000	0.000	0.000	0.000	1.000
190	1.000	0.000	0.000	0.000	1.000
200	1.000	0.000	0.000	0.000	1.000
225	1.000	0.000	0.000	0.000	1.000

Table 1-4
Aggregate

Pressure (psig)	Cumul. Fail. Prob.	Prob. Density	Conditional Probabilities for Failure Mode: Leak	Rupture (Hoop)	Rupture (Shear)	Catastrophic Rupture
50	0.000	0.000	1.000	0.000	0.000	0.000
60	0.003	0.003	0.980	0.000	0.020	0.000
70	0.010	0.007	0.960	0.000	0.040	0.000
80	0.025	0.015	0.946	0.000	0.054	0.000
90	0.043	0.018	0.938	0.000	0.062	0.000
100	0.067	0.024	0.940	0.000	0.060	0.000
110	0.107	0.040	0.927	0.000	0.073	0.000
120	0.207	0.100	0.750	0.187	0.030	0.033
130	0.398	0.191	0.775	0.146	0.024	0.055
140	0.843	0.445	0.156	0.289	0.010	0.545
150	0.913	0.070	0.414	0.000	0.110	0.476
160	0.933	0.020	0.750	0.000	0.250	0.000
170	0.956	0.023	0.680	0.000	0.320	0.000
180	0.973	0.017	0.630	0.000	0.370	0.000
190	0.986	0.013	0.590	0.000	0.410	0.000
200	0.992	0.006	0.550	0.000	0.450	0.000
225	1.000	0.008	0.500	0.000	0.500	0.000

Table 1-5
Zion Static Failure Pressure
Joint Distribution for Containment Failure Pressure and Mode

	Joint Probability for Failure Pressure and Mode				
Pressure (psig)	Leak	Rupture (Hoop)	Rupture (Shear)	Catastrophic Rupture	Marginal
50	0.000	0.000	0.000	0.000	0.000
60	0.003	0.000	0.000	0.000	0.003
70	0.007	0.000	0.000	0.000	0.007
80	0.014	0.000	0.001	0.000	0.015
90	0.017	0.000	0.001	0.000	0.018
100	0.023	0.000	0.001	0.000	0.024
110	0.037	0.000	0.003	0.000	0.040
120	0.075	0.019	0.003	0.003	0.100
130	0.148	0.028	0.004	0.011	0.191
140	0.069	0.129	0.004	0.243	0.445
150	0.029	0.000	0.008	0.033	0.070
160	0.015	0.000	0.005	0.000	0.020
170	0.016	0.000	0.007	0.000	0.023
180	0.011	0.000	0.006	0.000	0.017
190	0.008	0.000	0.005	0.000	0.013
200	0.003	0.000	0.003	0.000	0.006
225	0.004	0.000	0.004	0.000	0.008
Marginal	0.479	0.176	0.055	0.290	1.000

Method of Aggregation

The desired form for the results of each expert was a table of cumulative failure probabilities for increments of 10 psig as shown in Table 1-1. When an expert provided cumulative probabilities for a range of pressures, the average of the cumulative probabilities for two adjacent ranges was assigned to the pressure which divided the ranges. For example, if an expert assigned a cumulative probability of 0.10 to failure in the pressure range from 60 psia to 70 psia, and a cumulative probability of 0.20 to failure in the pressure range from 70 psia to 80 psia, then a cumulative failure probability of 0.15 would be assigned to 70 psia. Interpolation was used to fill in other values. A similar technique was used for the conditional probabilities for the four failure modes. Where an expert had not considered a failure mode the probability associated with each pressure level was taken as zero.

To determine the aggregated cumulative failure probability at pressure i, p(avg,i), the average was used:

$$p(avg,i) = (p(1,i) + p(2,i) + p(3,i)) / 3$$

where p(j,i) is the cumulative probability for failure at pressure i provided by the jth expert. The aggregate conditional probability for failure mode m at pressure i, c(avg,i,m), was calculated by:

$$c(avg,i,m) = ([p(1,i)-p(1,i-1)] * c(1,i,m) + [p(2,i)-p(2,i-1)] * c(2,i,m) + [p(3,i)-p(3,i-1)] * c(3,i,m)) / 3 / [p(avg,i) - p(avg,i-1)]$$

where c(j,i,m) is the conditional probability of expert j for failure mode m at pressure i. At the lowest pressure, as for all other pressures, the values sum to one--since they are conditional probabilities they must add to one, even if the event on which they are conditional has zero probability. This method weights the conditional probability for each expert by the probability density at the pressure i. The probability density is the first derivative of the cumulative probability. The backward difference approximation is used for the derivative. The sum of the weighted conditional probabilities is normalized by the difference of the aggregated cumulative probability.

For the purposes of the Zion accident progression analysis, a joint distribution of failure mode and pressure is of greater utility in the sampling process than the probability of a given failure mode conditional on failure pressure. Table 1-5, which gives the probability (density) of failure and the joint probability for the four failure modes, was calculated from Table 1-4 using:

$$p(m,i) = p(i)\ p(m|i)$$

where p(m,i) is the joint distribution of failure mode m at pressure i, p(i) is the probability density at pressure i and p(m|i) is the conditional probability of failure mode m given pressure i.

Individual Elicitations for Issue 1

Expert A's Elicitation

Containment Failure at Zion

Description of Expert A's Rationale/Methodology

Expert A based his conclusions on an analysis of the mid-section of the cylindrical portion of the containment. His study of the drawings and the results of other analyses led him to conclude that this was the weakest portion of the containment. His primary references were the Sargent & Lundy (S&L) analysis[A-1] and the 1/6-scale model test at Sandia.[A-2] As with the other experts considering this issue, Expert A concluded that the three cases, described in Section 1, were indistinguishable; the pressure rises were slow enough that all the loadings were static, and the temperatures were well below those at which degradation of structural properties occurs. As the S&L analysis considered other failure locations, such as the dome and the cylinder basemat junction area, and concluded that the weakest part was the midsection of the cylinder, Expert A focused on that failure mode and considered the hoop stresses there in some detail. His estimate was that this captured about 90% of the failure probability. Expert A used the 1/6-scale model test results to conclude that, at 2% strain in locations away from penetrations, the strain in the liner close to penetrations was likely to cause a tear.

The occurrence of either a leak or a rupture precludes the later occurrence of catastrophic rupture. Once a liner tear has developed, Expert A would expect it to expand in size as pressure increased. This would make catastrophic rupture very unlikely once a liner tear or leak had developed, but the increase in size could change the tear from a leak to a rupture. Leaks are more likely than rupture at lower failure pressures, and rupture is more likely at the higher pressures.

Expert A concluded that the Zion containment was absolutely safe at 90 psig, and that failure was possible but unlikely at 110 psig. He arrived at the 110 psig figure by calculating that general yielding of the rebar occurred at 120 psig and subtracting 10 psig for aging, unknown construction defects, etc., to set this value for the lower bound for failure. As 1% hoop strain occurs at 132 psig and 2% hoop strain at 140 psig, Expert A expected failure to occur in this pressure range with a high probability. The strain in the rebar and the post-tensioned tendons is about the same. When the tendons fail, the rebar, already highly stressed, will also fail. At 4% strain, catastrophic rupture is very likely, but a leak should have developed at lower pressures in most cases. The following table gives Expert A's view of the response of the containment to increasing pressures.

Pressure (psig)	Response of the Containment
64	Loss of hoop prestress
70	Loss of vertical prestress
85	Concrete strength exceeded in hoop direction
114	Liner yields
120	Hoop rebar yields, and concrete strength exceeded in the vertical direction
132	Strain in hoop tendons = 1%
134	Vertical rebar yields, hoop strain in liner = 1%
140	Hoop strain in liner = 2%
149	Ultimate strain (5%) in hoop tendons

Results of Expert A's Elicitation

Expert A provided the following table for the failure probability and mode of failure. It gives the probability (density) of failure and the joint probability for three of the failure modes.

		Joint Probability		
Pressure (psig)	Failure Probability Density	Leak	Rupture (Hoop)	Catastrophic Rupture
90	0.00	0.00	0.00	0.00
110-115	0.03	0.03	0.00	0.00
115-120	0.10	0.08	0.02	0.00
120-130	0.17	0.09	0.06	0.02
130-135	0.25	0.10	0.10	0.05
135-140	0.25	0.05	0.13	0.07
140-145	0.19	0.01	0.03	0.15
145-150	0.01	0.00	0.00	0.01

No column is shown for shear rupture since Expert A did not believe this failure mode was credible.

The marginal probabilities of failure are 36% leak, 34% rupture, and 30% catastrophic rupture. This table was converted into a table of cumulative failure probabilities with conditional probabilities for the failure mode.

Pressure (psig)	Failure Probability Cumulative	Conditional Probability Leak	Rupture (Hoop)	Catastrophic Rupture
90	0.00	0.00	0.00	0.00
110-115	0.03	1.00	0.00	0.00
115-120	0.13	0.80	0.20	0.00
120-130	0.30	0.53	0.35	0.12
130-135	0.55	0.40	0.40	0.20
135-140	0.80	0.20	0.52	0.28
140-145	0.99	0.05	0.16	0.79
145-150	1.00	0.00	0.00	1.00

This distribution, based on ranges of pressures, was converted into cumulative failure probabilities for 10 psig increments (see Table 1-1), as described above.

REFERENCES

A-1. Sargent & Lundy, "Containment Structural Capability of Light Water Nuclear Power Plants," IDCOR Technical Report 10.1, Technology for Energy Corporation, Knoxville, TN, July 1983.

A-2. D. S. Horschel, Sandia National Laboratories, Letter to J. F. Costello, U.S. Nuclear Regulatory Commission, August 2, 1987.

Expert B's Elicitation

Containment Failure at Zion

Description of B's Rationale/Methodology

Expert B considered two failure locations. The first was at mid-height in the cylindrical portion of the containment. He judged that failure at this location would always result in a leak. The other failure location was a shear failure at the point where the cylinder joins the basemat. Failure at this location could result in either a leak or a rupture. Catastrophic rupture was deemed not credible.

Results of Expert B's Elicitation

Expert B gave the following table of probability density versus pressure range for the hoop stress failure of the cylinder. The cumulative probability was derived from the probability density, adjusted upward slightly to account for the fact that the densities only summed to 0.95.

Pressure (psig)	Probability Density	Cumulative Probability
75-100	0.05	0.05
100-125	0.15	0.20
125-150	0.40	0.60
150-175	0.20	0.80
175-200	0.10	0.90
200-225	0.05	0.95
225-250	0.05	1.00

This failure mode depends only on the tendon yield and the ultimate hoop strength. At the ultimate strength of the average tendon, the pressure differential is 136 psig. Expert B thought that his midpoint f ilure pressure should be around this value. As all tendons were tested, he took 90% of 136 psig as the pressure representative of the 20% to 25% range of failure probability. Failure at these relatively low pressures could occur because of construction defects, material defects, or deterioration of the structures as it ages. For the 75% to 80% failure probability range, he added 30% to the 136 psig value to get 177 psig. He then drew a smooth curve through these points and estimated the values in the table above.

Converting the table of pressure ranges to specific pressures gives:

Pressure (psig)	Cumulative Probability of Cylinder Failure (Leak)
75	0.00
100	0.13
125	0.42
150	0.73
175	0.90
200	0.98
225	1.00

For the shear failure at the cylinder-basemat junction, both leak and rupture are possible but catastrophic rupture is not credible. Expert 3 gave the following table of probability density versus pressure range for this failure location, including conditional leak-rupture probabilities. The cumulative probability distribution in the following table is derived from the probability density distribution.

			Conditional Probability	
Pressure (psig)	Probability Density	Cumulative Probability	Leak	Rupture (Shear)
50-75	0.05	0.05	1.00	0.00
75-100	0.10	0.15	0.90	0.10
100-125	0.20	0.35	0.90	0.10
125-150	0.30	0.65	0.75	0.25
150-175	0.20	0.85	0.40	0.60
175-200	0.10	0.95	0.20	0.80
200-225	0.05	1.00	0.00	1.00

Failure at the junction of the cylinder and the basemat is possible because of the shear discontinuity at this location. The likelihood of shear failure depends on the extent of cracking in the concrete and the compressive stress developed in the concrete. In the following table, the parameter α represents the extent of concrete cracking: $\alpha = 0.1$ indicates extensive cracking and $\alpha = 1.0$ indicates no cracking. Variations in α, the shear strength, and the tendon yield were considered as follows:

Quantity	Low	Middle	High
Parameter α	0.10	0.25	1.00
Shear Capacity	$2(\rho_c)^{.5}$	$3(\rho_c)^{.5}$	$5(\rho_c)^{.5}$
Tendon Yield	$.9\ \sigma_{avg}$	σ_{avg}	$1.3\ \sigma_{avg}$
Failure Pressure due to Base Shear (psig)	80	102	160

The distribution of probability density and failure pressure ranges given above was constructed based on these numbers. Rupture is more likely at the higher pressures since the length of the failure is expected to be longer if it occurs at high pressure.

Pressure (psig)	Cumulative Shear Failure Probability	Conditional Probability Leak	Conditional Probability Rupture (Shear)
50	0.00	1.00	0.00
75	0.10	0.95	0.05
100	0.25	0.90	0.10
125	0.50	0.825	0.175
150	0.75	0.575	0.425
175	0.90	0.30	0.70
200	0.975	0.10	0.90
225	1.00	0.00	0.00

Finally, the cylindrical hoop failure table is combined with the shear failure table to get one table that includes the effects of both failure modes.

The total failure probability for a given pressure is the average of the cylinder and shear failure probabilities. The conditional probabilities for mode of failure (hole size) are averages weighted by the probabilities. The equation used is similar to the one presented in the Discussion section above.

Pressure (psig)	Cumulative Shear Failure Probability	Conditional Probability Leak	Conditional Probability Rupture (Shear)
50	0.00	1.00	0.00
75	0.05	0.95	0.05
100	0.19	0.93	0.07
125	0.46	0.90	0.10
150	0.74	0.78	0.22
175	0.90	0.65	0.35

No column is shown for either hoop rupture or catastrophic rupture since Expert B did not believe these failure modes were credible. Converting the table based on pressure ranges to one for specific pressures by interpolation produces the results shown in Table 1-2.

Expert C's Elicitation

Containment Failure at Zion

Description of Expert C's Rationale/Methodology

Expert C considered all three cases together since he felt that the previous pressures are irrelevant and that the temperatures are expected to be low. His main emphasis was on hoop stress in the cylindrical portion of the containment, but noted that bellows failure would be expected at 139 psig, which would result in a direct release to the environment. Liner tears at penetrations might result in releases into the auxiliary building.

The following table gives Expert C's view of the response of the containment to increasing internal pressures:

Pressure (psig)	Response of the Containment
47	Design Pressure
54	Test Pressure
75	Concrete Cracking
120	Yield--Liner not Considered
128	Failure--Liner not Considered
134	1% Strain--Liner Considered
136	Penetration Failure
138	Failure--Liner Considered
139	Bellows Failure
140	Ultimate Strain (4%)

Expert C's calculations showed that the liner carries 14 psig. He would subtract 1 psig for temperatures above 600°F and would subtract 3 psig for general uncertainty.

The lowest pressure at which Expert C would expect to see any significant chance of failure is at 128 psig, the pressure at which failure is predicted without taking the strength of the liner into account. Failure is assured by 137 psig. The failure distribution is narrow because yield in the hoop tendons starts at 134 psig and deformation then increases very quickly with increasing pressure. Deformations of 26 in. are expected by 143 psig.

Results of Expert C's Elicitation

Expert C's distribution is contained in the following table:

Pressure (psig)	Cumulative Failure Probability	Conditional Probability: Leak	Rupture (Hoop)	Catastrophic Rupture
120	0.0	1.0	0.0	0.0
128	0.2	1.0	0.0	0.0
134	0.4	0.9	0.1	0.0
135	0.6	0.8	0.2	0.0
136	0.9	0.6	0.3	0.1
137	1.0	0.4	0.4	0.2
138	1.0	0.2	0.5	0.3
139	1.0	0.1	0.4	0.5
143	1.0	0.0	0.0	1.0

No column is shown for shear rupture since Expert C did not believe this failure mode was credible. The entire failure probability is contained in the range from 120 psig to 137 psig. The conditional probabilities for failure mode above 137 psig are interpreted to mean that, if a rapid pressure rise results in peak pressures above 137 psig, these failure mode probabilities apply.

If the leak that develops is not sufficiently large to arrest the pressure rise, Expert C felt that the liner tear would increase in size until the opening was large enough to arrest the pressure rise. He was certain that a catastrophic rupture would not occur once a leak had developed; catastrophic rupture occurs, then, only in the very few cases where the pressure exceeds 137 psig without a leak developing. The table above was used to construct Table 1-3

5.2 Issue 2. Containment Failure at Surry

Experts consulted: Joe Rashid, ANATECH Research Corporation; Richard Toland, United Engineers & Constructors; Adolph Walser, Sargent & Lundy; Joe R. Weatherby, Sandia National Laboratories.

Issue Description

What distribution characterizes the failure pressures for static loading of the Surry containment? What conditional probabilities describe the failure modes for each pressure?

The Surry containment is a cylinder with a hemispherical dome roof. Both the cylinder and the dome are constructed of reinforced concrete. The foundation is a reinforced concrete slab. The containment is lined with welded 0.25-in. plate steel. The containment is maintained below ambient atmospheric pressure, at about 10 psia, during operation. The design pressure is 45 psig. The free volume is about 1,850,000 ft^3.

Three pressure rise cases were described in the original definition of the issue:

1. Pressure spike at vessel breach,
2. Late deflagration, and
3. Late, gradual pressure rise.

Typical rise times for cases 1 and 2 would be on the order of a few seconds. Typical rise times for case 3 would be on the order of an hour. While very high atmospheric temperatures might be observed for a fraction of a minute in case 1, the bulk temperature of the steel liner which forms the pressure boundary is not expected to exceed 300 to 350°F.

The original issue definition of a large hole or rupture was an opening larger than 1.0 ft^2, which resulted in depressurization in less than about 2 h. A small hole or leak was anything smaller than 1.0 ft^2, which did not result in depressurization in less than about 2 h. A review of this matter showed that large dry containments would depressurize in 2 h for holes sizes on the order of 0.3 to 0.5 ft^2. Thus a small hole or leak should have been on the order of 0.1 ft^2, and 1.0 ft^2 is definitely a large hole or rupture. The panel members were asked to reconsider the distributions they provided in light of this redefinition of the hole size. Some of them adjusted their distributions for this or for some other reason.

The failure mode "Catastrophic Rupture" (CR) was added at the time of elicitation. Catastrophic rupture implies complete failure of a substantial portion of the containment pressure boundary, with possible disruption of the piping systems that penetrate or are attached to the containment wall. No similar gross structural failure is implied by the "Rupture" failure mode.

Summary of Results

The four panel members considering this issue all agreed that the three cases could be considered together since the pressure rise times were slow enough that the effects were all static. It was pointed out to the experts that the development of a leak would not arrest the pressure rise for cases 1 and 2, but they did not choose to provide separate distributions for these two cases. However, some of the experts allowed for the possibility that the development of a leak would not arrest the pressure rise by providing rupture and CR probabilities for pressures greater than the pressure for which they thought the development of a leak was certain.

The experts also agreed that there was no need to differentiate between cases on the basis of temperature. The temperatures stated were all low enough that there would be no appreciable structural effect; i.e., no significant changes in material properties occur at the temperatures in question.

Failure location did not turn out to be important since any failure location except shear at the basemat-cylinder junction would result in a direct path to the outside. The reinforcing and concrete details in this junction area were such that three of the four experts ruled out failure in this location. (The fourth expert did not specify failure location explicitly.)

The distributions of the four experts for the containment failure pressure and mode for Surry, as received, are given in Tables A-1, B-1, C-1, and D-1. Experts A and B gave cumulative failure probabilities and interval conditional probabilities for the mode of failure. Their distributions are shown in Tables A-1 and B-1, respectively. Expert A concluded that the containment would fail between 120 and 150 psig. His median value was 135 psig. At 145 psig, he viewed leak, rupture, and CR as about equally likely. He allowed for pressurization above 150 psig by rapid pressure rise by shifting his conditional failure mode probabilities toward CR above 150 psig.

Expert B concluded that the containment would fail between 70 and 165 psig. His median value was 120 psig. The lower end of his distribution allows for faulty cadwelds and liner tears due to stress concentrations around openings. He thought the leak failure mode was most likely if the containment failed below 125 psig, the rupture mode was most likely for failure between 125 and 155 psig, and CR was most likely above 155 psig. Although he was certain that some failure would occur by 165 psig, he allowed for pressurization above this value by rapid pressure rise by shifting his conditional failure mode probabilities toward certain CR above 165 psig.

Expert C gave joint interval probabilities, or joint probability densities, as shown in second, third, and fourth columns of Table C-1. These values were converted to total cumulative failure probabilities with interval conditional probabilities for failure mode as shown in Table C-2. Expert C was virtually certain that containment failure would occur between 125 and 165 psig, although he allowed a 1% probability that the failure might occur as high as 200 psig.

Table A-1
Surry Static Failure Pressure as Received from Expert A

Pressure (psig)	Cumulative Failure Probability	Failure Prob. Density	Interval Conditional Prob. Leak	Interval Conditional Prob. Rupture	Interval Conditional Prob. Cat.Rup.
60	0.000	0.000	1.000	0.000	0.000
65	0.000	0.000	1.000	0.000	0.000
70	0.000	0.000	1.000	0.000	0.000
75	0.000	0.000	1.000	0.000	0.000
80	0.000	0.000	1.000	0.000	0.000
85	0.000	0.000	1.000	0.000	0.000
90	0.000	0.000	1.000	0.000	0.000
95	0.000	0.000	1.000	0.000	0.000
100	0.000	0.000	1.000	0.000	0.000
105	0.000	0.000	1.000	0.000	0.000
110	0.000	0.000	1.000	0.000	0.000
115	0.000	0.000	1.000	0.000	0.000
120	0.010	0.010	1.000	0.000	0.000
125	0.167	0.157	0.833	0.167	0.000
130	0.333	0.166	0.667	0.333	0.000
135	0.500	0.167	0.500	0.500	0.000
140	0.670	0.170	0.400	0.433	0.167
145	0.830	0.160	0.300	0.367	0.333
150	1.000	0.170	0.200	0.300	0.500
155	1.000	0.000	0.120	0.255	0.625
160	1.000	0.000	0.070	0.180	0.750
165	1.000	0.000	0.040	0.085	0.875
170	1.000	0.000	0.000	0.000	1.000
175	1.000	0.000	0.000	0.000	1.000
180	1.000	0.000	0.000	0.000	1.000
185	1.000	0.000	0.000	0.000	1.000
190	1.000	0.000	0.000	0.000	1.000
195	1.000	0.000	0.000	0.000	1.000
200	1.000	0.000	0.000	0.000	1.000

Table B-1
Surry Static Failure Pressure as Received from Expert B

Pressure (psig)	Cumulative Failure Probability	Failure Prob. Density	Interval Conditional Prob. Leak	Rupture	Cat.Rup.
60	0.000	0.000	1.000	0.000	0.000
65	0.000	0.000	1.000	0.000	0.000
70	0.001	0.001	1.000	0.000	0.000
75	0.010	0.009	0.950	0.050	0.000
80	0.020	0.010	0.900	0.100	0.000
85	0.030	0.010	0.850	0.150	0.000
90	0.050	0.020	0.800	0.200	0.000
95	0.110	0.060	0.767	0.233	0.000
100	0.180	0.070	0.733	0.267	0.000
105	0.250	0.070	0.700	0.300	0.000
110	0.330	0.080	0.667	0.333	0.000
115	0.410	0.080	0.633	0.367	0.000
120	0.500	0.090	0.600	0.400	0.000
125	0.620	0.120	0.433	0.533	0.034
130	0.740	0.120	0.267	0.667	0.066
135	0.850	0.110	0.100	0.800	0.100
140	0.900	0.050	0.083	0.750	0.167
145	0.950	0.050	0.067	0.700	0.233
150	0.990	0.040	0.050	0.650	0.300
155	0.994	0.004	0.033	0.500	0.467
160	0.997	0.003	0.017	0.350	0.633
165	1.000	0.003	0.000	0.200	0.800
170	1.000	0.000	0.000	0.100	0.900
175	1.000	0.000	0.000	0.000	1.000
180	1.000	0.000	0.000	0.000	1.000
185	1.000	0.000	0.000	0.000	1.000
190	1.000	0.000	0.000	0.000	1.000
195	1.000	0.000	0.000	0.000	1.000
200	1.000	0.000	0.000	0.000	1.000

Table C-1
Surry Static Failure Pressure as Received from Expert C

Pressure (psig)	Joint Interval Probability Leak	Rupture	Cat.Rup.	Failure Prob. Density	Cumulative Failure Probability
60	0.000	0.000	0.000	0.000	0.000
65	0.000	0.000	0.000	0.000	0.000
70	0.000	0.000	0.000	0.000	0.000
75	0.000	0.000	0.000	0.000	0.000
80	0.000	0.000	0.000	0.000	0.000
85	0.000	0.000	0.000	0.000	0.000
90	0.000	0.000	0.000	0.000	0.000
95	0.000	0.000	0.000	0.000	0.000
100	0.000	0.000	0.000	0.000	0.000
105	0.000	0.000	0.000	0.000	0.000
110	0.000	0.000	0.000	0.000	0.000
115	0.000	0.000	0.000	0.000	0.000
120	0.000	0.000	0.000	0.000	0.000
125	0.010	0.005	0.000	0.015	0.015
130	0.020	0.010	0.000	0.030	0.045
135	0.040	0.015	0.000	0.055	0.100
140	0.180	0.120	0.000	0.300	0.400
145	0.110	0.130	0.030	0.270	0.670
150	0.060	0.090	0.040	0.190	0.860
155	0.020	0.030	0.040	0.090	0.950
160	0.000	0.005	0.015	0.020	0.970
165	0.000	0.005	0.015	0.020	0.990
170	0.000	0.000	0.002	0.002	0.992
175	0.000	0.000	0.002	0.002	0.994
180	0.000	0.000	0.002	0.002	0.996
185	0.000	0.000	0.001	0.001	0.997
190	0.000	0.000	0.001	0.001	0.998
195	0.000	0.000	0.001	0.001	0.999
200	0.000	0.000	0.001	0.001	1.000
Total	0.440	0.410	0.150		

Table D-1
Surry Static Failure Pressure as Received from Expert D

Pressure (psig)	Independent Failure Prob. Leak	Rupture	Cat.Rup.	Cumulative Failure Probability	Failure Prob. Density
60	0.000	0.000	0.000	0.000	0.000
65	0.000	0.000	0.000	0.000	0.000
70	0.000	0.000	0.000	0.000	0.000
75	0.000	0.000	0.000	0.000	0.000
80	0.020	0.000	0.000	0.020	0.020
85	0.050	0.000	0.000	0.050	0.030
90	0.075	0.000	0.000	0.075	0.025
95	0.125	0.000	0.000	0.125	0.050
100	0.200	0.000	0.000	0.200	0.075
105	0.300	0.000	0.000	0.300	0.100
110	0.500	0.000	0.000	0.500	0.200
115	0.850	0.000	0.000	0.850	0.350
120	0.950	0.000	0.000	0.950	0.100
125	0.980	0.000	0.000	0.980	0.030
130	1.000	0.000	0.000	1.000	0.020
135	1.000	0.000	0.000	1.000	0.000
140	1.000	0.000	0.000	1.000	0.000
145	1.000	0.050	0.000	1.00	0.000
150	1.000	0.200	0.000	1.000	0.000
155	1.000	0.500	0.000	1.000	0.000
160	1.000	0.800	0.000	1.000	0.000
165	1.000	0.950	0.000	1.000	0.000
170	1.000	1.000	0.000	1.000	0.000
175	1.000	1.000	0.000	1.000	0.000
180	1.000	1.000	0.000	1.000	0.000
185	1.000	1.000	0.000	1.000	0.000
190	1.000	1.000	0.000	1.000	0.000
195	1.000	1.000	0.000	1.000	0.000
200	1.000	1.000	0.000	1.000	0.000

Table C-2
Joint Interval Probabilities and Modifications to Total Cumulative Probabilities

Pressure (psig)	Cumulative Failure Probability	Failure Prob. Density	Interval Conditional Prob. Leak	Interval Conditional Prob. Rupture	Interval Conditional Prob. Cat.Rup.
60	0.000	0.000	0.667	0.333	0.000
65	0.000	0.000	0.667	0.333	0.000
70	0.000	0.000	0.667	0.333	0.000
75	0.000	0.000	0.667	0.333	0.000
80	0.000	0.000	0.667	0.333	0.000
85	0.000	0.000	0.667	0.333	0.000
90	0.000	0.000	0.667	0.333	0.000
95	0.000	0.000	0.667	0.333	0.000
100	0.000	0.000	0.667	0.333	0.000
105	0.000	0.000	0.667	0.333	0.000
110	0.000	0.000	0.667	0.333	0.000
115	0.000	0.000	0.667	0.333	0.000
120	0.000	0.000	0.667	0.333	0.000
125	0.015	0.015	0.667	0.333	0.000
130	0.045	0.030	0.667	0.333	0.000
135	0.100	0.055	0.727	0.273	0.000
140	0.400	0.300	0.600	0.400	0.000
145	0.670	0.270	0.407	0.481	0.111
150	0.860	0.190	0.316	0.474	0.211
155	0.950	0.090	0.222	0.333	0.444
160	0.970	0.020	0.000	0.250	0.750
165	0.990	0.020	[illegible]	0.250	0.750
170	0.992	0.002	0.000	0.000	1.000
175	0.994	0.002	0.000	0.000	1.000
180	0.996	0.002	0.000	0.000	1.000
185	0.997	0.001	0.000	0.000	1.000
190	0.998	0.001	0.000	0.000	1.000
195	0.999	0.001	0.000	0.000	1.000
200	1.000	0.001	0.000	0.000	1.000

At 125 psig, he thought that failure was twice as likely to be rupture as leak. At 165 psig he thought that CR was three times as likely as rupture. The three failure modes are approximately equal in the 150 to 155 psig range.

Expert D gave independent failure probabilities for leak and rupture as shown in Table D-1. These values were converted to total cumulative failure probabilities with interval conditional probabilities for failure mode as shown in Table D-2. Expert D did not believe that catastrophic ruptures were credible at Surry. Expert D also believed that only leaks were credible if the containment failed below 140 psig, and that only ruptures were credible if the containment failed above 140 psig. He also was certain that a leak would develop by 130 psig.

Table 2-1 gives the aggregate distribution. The median failure pressure is about 128 psig. Leak is the most likely failure mode below that value. Rupture is the most likely failure mode if the containment fails around 135 to 150 psig. Above 155 psig, catastrophic rupture is the most likely failure mode. The method of aggregation used to form Table 2-1 is described in the next section. The conditional failure probabilities may sum to 0.999 or 1.001 rather than 1.000 because of roundoff errors. Although one of the four experts believed that CR was not a credible failure mode at Surry, his failure probability density was zero for the higher failure pressures. Thus, the conditional probability of catastrophic rupture goes to 1.0 at the highest pressures.

Figure 2-1 shows the distributions of the four experts and the aggregate distribution for total cumulative failure probability. There is little agreement among the experts. Note that Experts A and C concluded that there is little or no chance of failure by 120 psig, while Expert D concluded that failure is almost certain by 120 psig.

Figure 2-2 shows the distributions of the four experts and the aggregate distribution for the conditional probability of leak. There is general agreement among the experts that if the containment fails at the lower end of the pressure range, leak is the most likely failure mode.

Figure 2-3 shows the distributions of the four experts and the aggregate distribution for the conditional probability of rupture. There is general agreement among three of the experts that if the containment fails near the middle of the pressure range, rupture is the most likely failure mode. Expert D felt that rupture was certain if the containment failed above 140 psig.

Figure 2-4 shows the distributions of the four experts and the aggregate distribution for the conditional probability of catastrophic rupture. There is general agreement among three of the experts that if the containment fails at the upper end of the pressure range, CR is most likely failure mode. Expert D did not believe that CR was a credible failure mode at Surry.

Table D-2
Joint Interval Probabilities and Modifications to
Total Cumulative Probabilities

Pressure (psig)	Cumulative Failure Probability	Failure Prob. Density	Interval Conditional Prob.		
			Leak	Rupture	Cat.Rup.
60	0.000	0.000	1.000	0.000	0.000
65	0.000	0.000	1.000	0.000	0.000
70	0.000	0.000	1.000	0.000	0.000
75	0.000	0.000	1.000	0.000	0.000
80	0.020	0.020	1.000	0.000	0.000
85	0.050	0.030	1.000	0.000	0.000
90	0.075	0.025	1.000	0.000	0.000
95	0.125	0.050	1.000	0.000	0.000
100	0.200	0.075	1.000	0.000	0.000
105	0.300	0.100	1.000	0.000	0.000
110	0.500	0.200	1.000	0.000	0.000
115	0.850	0.350	1.000	0.000	0.000
120	0.950	0.100	1.000	0.000	0.000
125	0.980	0.030	1.000	0.000	0.000
130	1.000	0.020	1.000	0.000	0.000
135	1.000	0.000	1.000	0.000	0.000
140	1.000	0.000	1.000	0.000	0.000
145	1.000	0.000	0.000	1.000	0.000
150	1.000	0.000	0.000	1.000	0.000
155	1.000	0.000	0.000	1.000	0.000
160	1.000	0.000	0.000	1.000	0.000
165	1.000	0.000	0.000	1.000	0.000
170	1.000	0.000	0.000	1.000	0.000
175	1.000	0.000	0.000	1.000	0.000
180	1.000	0.000	0.000	1.000	0.000
185	1.000	0.000	0.000	1.000	0.000
190	1.000	0.000	0.000	1.000	0.000
195	1.000	0.000	0.000	1.000	0.000
200	1.000	0.000	0.000	1.000	0.000

Table 2-1
Aggregate: Surry Static Failure Pressure

Pressure (psig)	Cumulative Failure Probability	Failure Prob. Density	Interval Conditional Prob. Leak	Rupture	Cat.Rup.
60	0.000	0.000	1.000	0.000	0.000
65	0.000	0.000	1.000	0.000	0.000
70	0.000	0.000	1.000	0.000	0.000
75	0.003	0.002	0.950	0.050	0.000
80	0.010	0.008	0.967	0.033	0.000
85	0.020	0.010	0.963	0.037	0.000
90	0.031	0.011	0.911	0.089	0.000
95	0.059	0.028	0.873	0.127	0.000
100	0.095	0.036	0.871	0.129	0.000
105	0.138	0.043	0.876	0.124	0.000
110	0.208	0.070	0.905	0.095	0.000
115	0.315	0.107	0.932	0.068	0.000
120	0.365	0.050	0.820	0.180	0.000
125	0.446	0.081	0.692	0.296	0.013
130	0.530	0.084	0.544	0.432	0.024
135	0.613	0.083	0.405	0.562	0.033
140	0.743	0.130	0.485	0.444	0.071
145	0.863	0.120	0.336	0.466	0.198
150	0.963	0.100	0.240	0.418	0.343
155	0.986	0.023	0.214	0.340	0.445
160	0.992	0.006	0.002	0.263	0.735
165	0.998	0.006	0.000	0.243	0.757
170	0.998	0.000	0.000	0.000	1.000
175	0.999	0.001	0.000	0.000	1.000
180	0.999	0.000	0.000	0.000	1.000
185	0.999	0.000	0.000	0.000	1.000
190	1.000	0.000	0.000	0.000	1.000
195	1.000	0.000	0.000	0.000	1.000
200	1.000	0.000	0.000	0.000	1.000

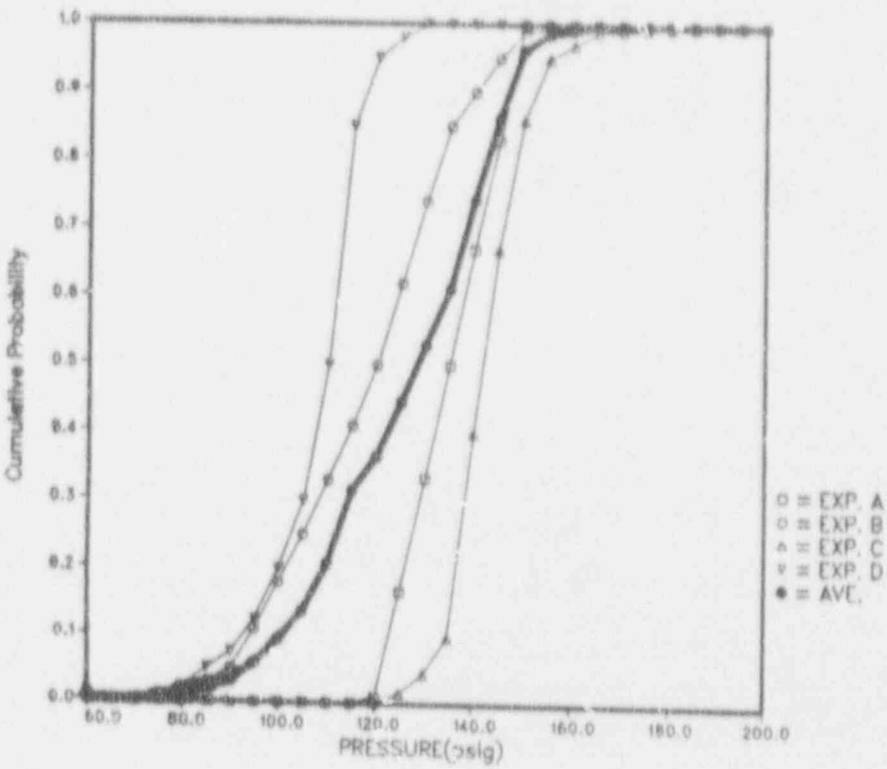

Figure 2-1. Cumulative Failure Probabilities.

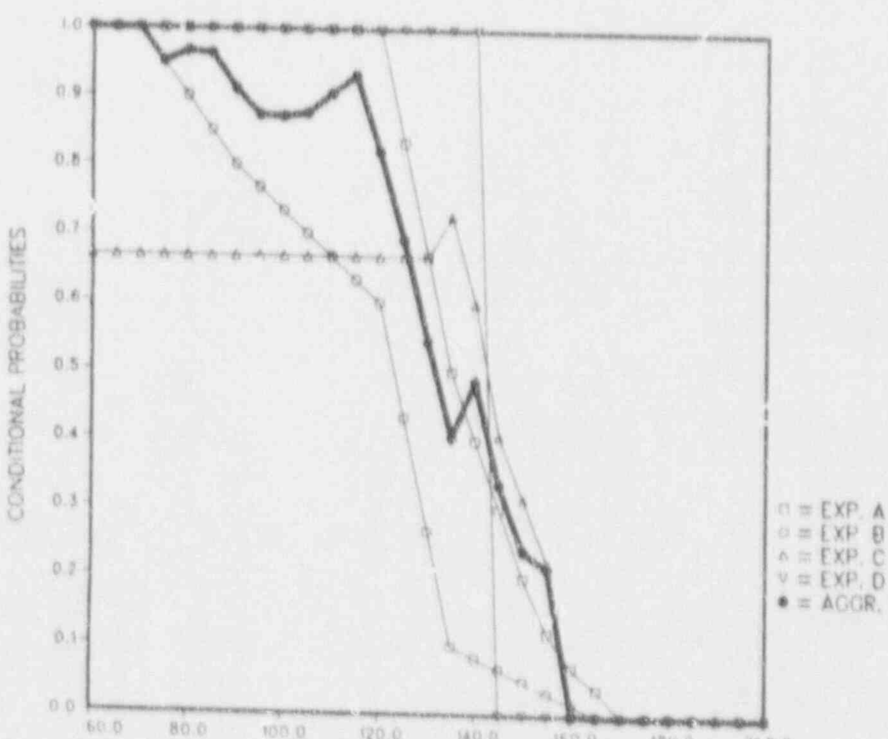

Figure 2-2. Conditional Probabilities of Leak.

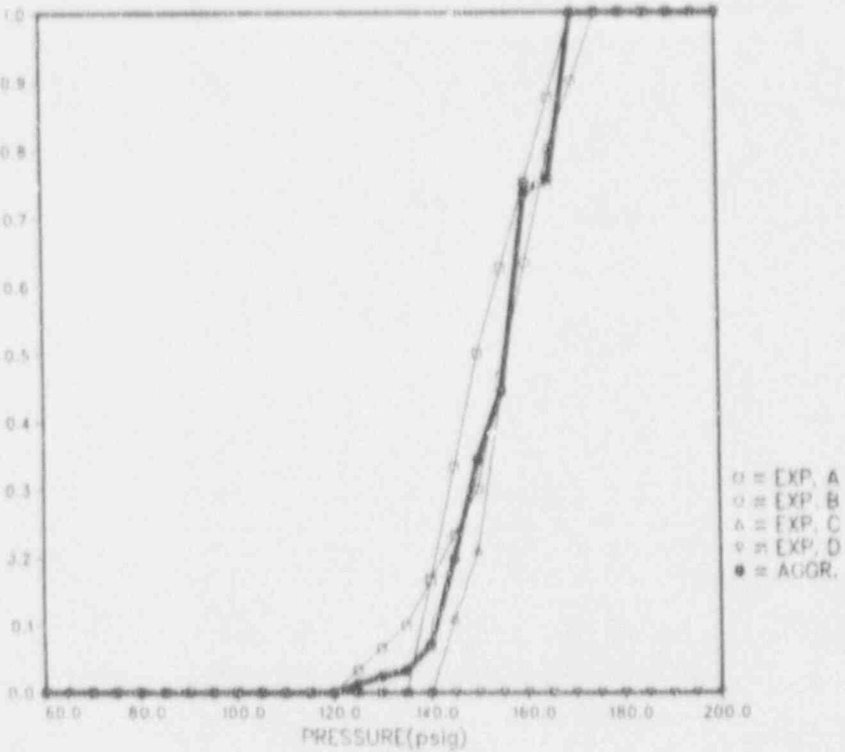

Figure 2-3. Conditional Probabilities of Catastrophic Rupture.

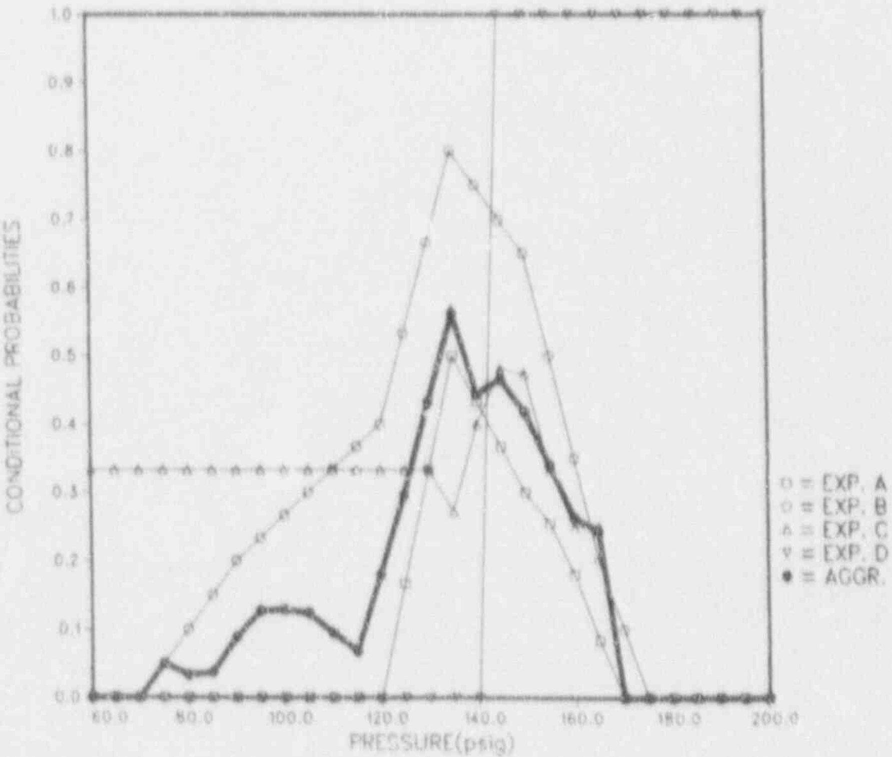

Figure 2-4. [illegible]nditional Probabilities of Rupture.

Method of Aggregation

Experts A and B gave cumulative failure probabilities and interval conditional probabilities for the mode of failure. Their distributions were in the proper form for aggregation. The cumulative failure probabilities are for all modes of containment failure. The distributions they provided were not for 5 psig increments, so interpolation has been used to fill in values.

Expert C gave joint interval probabilities, or joint probability densities, as shown in the second, third, and fourth columns of Table 1C. The failure probability density (FPD) column in Table 1C is the sum of the three joint interval probabilities for each pressure. The cumulative failure probability (CFP) column is formed by adding the FPD for the pressure interval in question to the CFP for the preceding pressure interval. The interval conditional probabilities for failure mode in Table 2C are formed by normalizing the joint interval probabilities in Table 1C.

Expert D gave independent cumulative failure probabilities for leak and rupture as shown in the second, third, and fourth columns of Table 1D. The cumulative failure probability column in Table 1D is formed by the equation:

$$CFP(i) = 1 [1-G_{lk}(i)] * [1-G_{rp}(i)] * [1-G_{cr}(i)]$$

for each pressure interval i,

where

CFP(i) is the total cumulative failure probability for interval i;

G_{lk} = the independent cumulative probability of leak failure for interval i;

G_{rp} = the independent cumulative probability of rupture failure for interval i;

and

G_{cr} = the independent cumulative probability of catastrophic rupture failure for interval i.

The interval conditional probabilities for failure mode in Table 2D are formed from the total cumulative failure probability and the independent failure probabilities. The equation for the interval conditional probability for leak, $C_{lk}(i)$, is:

$$C_{lk}(i) = [(2 - CFP(i) - CFP(i-1)) * (G_{lk}(i) - G_{lk}(i-1))] /$$

$$[(2 - G_{lk}(i) - G_{lk}(i-1)) * (CFP(i) - CFP(i-1))] .$$

The equations for the interval conditional probability for rupture and CR are analogous.

The aggregation of the cumulative failure probability is a straightforward averaging process. That is, the aggregate for the cumulative failure probability for each pressure interval is the average of the values in Tables A-1, B-1, C-2, and D-2. Note that the FPD is formed using the backward difference of the CFP because most of the experts referred to a pressure range by its upper bound.

For the interval conditional probabilities, the aggregate is formed by weighting each expert's interval conditional probability by the failure probability density for the interval. The equation used is:

$$C(i,m) = [C_A(i,m) * D_A(i) + C_B(i,m) * D_B(i) + C_C(i,m) * D_C(i) + C_D(i,m) * D_D(i)] / [D_A(i) + D_B(i) + D_C(i) + D_D(i)]$$

where

$C(i,m)$ is the aggregate conditional probability for failure in mode m, given that the failure occurs in pressure interval i;

$C_j(i,m)$ is Expert j's conditional probability for failure in mode m, given that the failure occurs in pressure interval i; and

$D_j(i)$ is Expert j's probability that the containment will fail in pressure interval i.

This can be shown to be equivalent to averaging the joint probabilities. The proof is as follows:

Let

$D(i)$ be the aggregate probability that the containment will fail in pressure interval i;

$J_j(i,m)$ be Expert j's joint probability that the containment will fail in pressure interval i and in failure mode m; and

$J(i,m)$ be the aggregate joint probability that the containment will fail in pressure interval i and in failure mode m.

Now

$$D(i) = [D_A(i) + D_B(i) + D_C(i) + D_D(i)] / 4$$

and

$$J(i,m) = [J_A(i,m) + J_B(i,m) + J_C(i,m) + J_D(i,m)] / 4.$$

The relationship between the failure probability density, D, the joint failure probability, J, and the conditional failure mode probability, C, is:

$$J(i,m) = D(i) * C(i,m).$$

This holds for each individual as well as for the aggregate. So

$$C(i,m) = J(i,m)/D(i) = \{[J_A(i,m) + J_B(i,m) + J_C(i,m) + J_D(i,m)]/4\}$$

$$/\{[D_A(i) + D_B(i) + D_C(i) + D_D(i)] / 4\}.$$

Using the relationship between the density, the joint, and the conditional probabilities for each expert this becomes

$$C(i,m) = [C_A(i,m) * D_A(i) + C_B(i,m) * D_B(i) + C_C(i,m) * D_C(i)$$

$$+ C_D(i,m) * D_D(i)] / [D_A(i) + D_B(i) + D_C(i) + D_D(i)]$$

as above.

Method of Determining Containment Failure

This section discusses the manner in which the results of the elicitations on this issue will be used in the event trees which follow the accident progression. For each observation in the sample, a sampling scheme selects a load pressure from a load distribution given by the Containment Loads Panel and selects a containment failure pressure from the aggregate curve given in Table 2-1. The sampling scheme also selects a random number between zero and one to be used to determine the mode of failure.

The load pressure and the containment failure pressure are compared by a user function in the event tree. If the load pressure is less than the containment failure pressure, the containment does not fail. If the load pressure is greater than or equal to the containment failure pressure, the containment fails. If the containment fails, the random number is used to determine the failure mode. Consider the following example: the failure pressure is 130 psig, the load pressure is 135 psig, and pressure rise is slow compared to the time it takes a leak to depressurize the containment. Since a leak at 130 psig will arrest the pressure rise, the interval conditional probability entries in Table 2-1 for 130 psig are used to determine the failure mode. The interval conditional probability for leak is 0.544, so if the random number is less than 0.544 the failure mode is leak. The interval conditional probability for rupture is 0.432, so if the random number is between 0.544 and 0.976 (= 0.544 + 0.432) the failure mode is rupture. If the random number exceeds 0.976, the failure mode is CR.

If the pressure rise is fast compared to the time it takes a leak to depressurize the containment, the determination of the failure mode is more complicated. Again consider the example in which the failure pressure is 130 psig and the load pressure is 135 psig. If a leak develops at 130 psig, the pressure will keep on rising, and a rupture or CR may develop between 130 and 135 psig. To determine the appropriate failure probability density, the portion of the distribution below 130 psig is discounted since failure has occurred at 130 psig. Thus the density used to determine if an additional rupture may occur between 130 and 135 psig is not FPD(135) = 0.083, but FPD(135) / (1 - CFP(130)) = 0.083 /(1 - 0.530) = 0.177. The conditional probability of additional ruptures forming between 130 and 135 psig is the leak probability at 130 psig times the conditional rupture probability for the 135 psig interval times the appropriate failure density. For the conditional probability, the average of the values for 130 and 135 psig is used: (0.432 + 0.562) / 2 = 0.497. Thus, the total conditional probability of rupture, for rapid pressure rise with a failure pressure of 130 psig and a load pressure of 135 psig, is:

$$0.432 + 0.544 * 0.497 * 0.177 = 0.480.$$

In general terms, this is:

$$R_{rp}(i) = R_{rp}(i-1) + R_{lk}(i-1) * 0.5 * (C_{rp}(i) + C_{rp}(i-1))$$

$$* FPD(i) / (1 - CFP(i-1))$$

where C_{rp}, FPD, and CFP have been defined above and R_{rp} and R_{lk} are the interval conditional probabilities of rupture and leak for fast pressure rise. This equation, and an analogous one for R_{cr}, the interval conditional probability of catastrophic rupture for fast pressure rise, have been used to generate the values shown in Table 2-2. After R_{rp} and R_{cr} have been found, the remaining leak fraction is found from:

$$R_{lk}(i) = 1 - R_{rp}(i) - R_{cr}(i).$$

For a rapid pressure rise, a failure pressure of 130 psig, and a load pressure of 135 psig, the conditional probabilities of leak, rupture, and CR are 0.494, 0.480, and 0.026, respectively, as shown on the appropriate line in Table 2-2. To determine the mode of containment failure for fast pressure rise, the random number is used as it is for slow pressure rise. In our example with a rapid pressure rise, a failure pressure of 130 psig, and a load pressure of 135 psig, if the random number is less than 0.494 the failure mode is leak. If the random number is between 0.494 and 0.974 (= 0.494 + 0.480) the failure mode is rupture. If the random number exceeds 0.974, the failure mode is CR.

Table 2-2 shows the failure mode probabilities for rapid pressure rise for two failure pressures, 75 psig and 130 psig, for all load pressures. Successive applications of the equation given above for R_{rp} and the analogous equation for R_{cr} determine the entries for each row based on the row above and the entries in Table 2-1. Zeros have been entered for the failure mode probabilities in Table 2-2 where the load pressure is below the failure pressure as there is no containment failure in these cases. In a few rows in Table 2-2, the failure mode probabilities add to 0.999 or 1.001 instead of 1.000. This is due to roundoff error.

Two questions may be asked about Table 2-2. First, why do the failure mode probabilities not go to the upper limit values shown in Table 2-1? Second, why is there still a possibility of leak at 175 psig when Table 2-1 shows a zero conditional probability for leak at that pressure?

Table 2-2
Surry Static Failure Pressure
Failure Mode Probabilities for Rapid Pressure Rise

Load Pres. (psig)	Failure Mode Probabilities (Failure Prob. = 75 psig)			Failure Mode Probabilities (Failure Prob. = 130 psig)		
	Leak	Rupture	Cat.Rup.	Leak	Rupture	Cat.Rup.
60	0.000	0.000	0.000	0.000	0.000	0.000
65	0.000	0.000	0.000	0.000	0.000	0.000
70	0.000	0.000	0.000	0.000	0.000	0.000
75	0.950	0.050	0.000	0.000	0.000	0.000
80	0.950	0.050	0.000	0.000	0.000	0.000
85	0.949	0.051	0.000	0.000	0.000	0.000
90	0.949	0.051	0.000	0.000	0.000	0.000
95	0.946	0.054	0.000	0.000	0.000	0.000
100	0.941	0.059	0.000	0.000	0.000	0.000
105	0.936	0.064	0.000	0.000	0.000	0.000
110	0.927	0.073	0.000	0.000	0.000	0.000
115	0.917	0.083	0.000	0.000	0.000	0.000
120	0.909	0.091	0.000	0.000	0.000	0.000
125	0.881	0.119	0.001	0.000	0.000	0.000
130	0.830	0.167	0.003	0.544	0.432	0.024
135	0.753	0.240	0.007	0.494	0.480	0.026
140	0.613	0.367	0.020	0.402	0.563	0.035
145	0.444	0.497	0.059	0.291	0.649	0.060
150	0.214	0.640	0.146	0.140	0.742	0.117
155	0.110	0.691	0.199	0.072	0.776	0.152
160	0.070	0.704	0.226	0.046	0.785	0.169
165	0.021	0.717	0.262	0.014	0.793	0.193
170	0.017	0.717	0.266	0.011	0.793	0.196
175	0.013	0.717	0.270	0.008	0.793	0.199
180	0.009	0.717	0.274	0.006	0.793	0.201
185	0.006	0.717	0.276	0.004	0.793	0.203
190	0.004	0.717	0.279	0.003	0.793	0.204
195	0.002	0.717	0.281	0.001	0.793	0.206
200	0.000	0.717	0.283	0.000	0.793	0.207

The first question may be phrased: why don't the entries for 180 to 200 psig in Table 2-2 show 0.0 for rupture and 1.00 for CR as in Table 2-1? The answer is that the results shown in Table 2-2 come from a much different type of calculation. For rapid pressure rise, the fraction of leaks that are still leaks at 180 psig, and for which an additional failure is calculated at 180 psig, are all CR as indicated in Table 2-1. Table 2-2 shows the results of working up in pressure from 75 and 130 psig to the load pressures shown in the left column. Ruptures are much more likely than CRs up to 140 psig pressure range. Thus, from 110 to 150 psig, where the FPD is relatively large, a much larger fraction of a leak failure is converted to ruptures than is converted to CRs.

The second question is: why is there a small but nonzero probability of leak for 175 to 200 psig in Table 2-2 when Table 2-1 shows a zero conditional probability for leak for those pressures? The reason for this is that, of the leaks that occurred at 75 or 130 psig and are still leaks at 175 psig, the fraction that has an additional failure at 175 psig is less than 1.00. There is still a small probability of failure above 175 psig, or 180 psig, etc. The nonzero entries for leak above 170 psig merely indicate that the CFP has not gone to 1.000 exactly at 175 psig. As there is some probability density above 170 psig, then there is some chance that the leak will not be converted to rupture or CR at 175 psig, or 180 psig, etc. Thus there are nonzero entries for leak above 170 psig.

Individual Elicitations for Issue 2

Expert A's Elicitation

Containment Failure at Surry

Description of Expert A's Rationale/Methodology

Expert A found the available information for Surry to be less than that available for Zion, and would have preferred more information. Based on the failure modes found to be important in studies of similar containments, e.g., Indian Point,[A-1] Expert A considered four failure modes:

- Hoop--in the cylinder;
- Hoop--in the dome;
- Shear--at the cylinder-basemat junction;
- Penetrations.

Meridional failure in the dome will be similar to the hoop failure and was not considered explicitly. On the basis of the detailed drawings and some calculations he made, Expert A concluded that the cylinder-basemat junction was a very strong region and ruled out failure at this location. He looked briefly at the equipment hatch, personnel airlock, pipe penetrations, and electrical penetrations. He concluded that they were sufficiently similar to those at Zion that failure at one of those locations was of low enough probability that it could be dismissed from further consideration.

The way the rebar was placed at the top of the dome led Expert A to question the strength of the dome at high stress levels. At low and medium stress levels, with the liner taken into account for both the cylinder and the dome, the dome is stronger than the cylinder.

For the cylinder, the hoop stress can adequately be calculated by hand. Expert A got 119 psig, which agrees with the Stone & Webster analysis.[A-2] This is the value for general yield of the rebar. This is the lowest pressure at which Expert A would expect to find any chance of failure: at this pressure the cylinder wall has moved out 2 in.

Expert A then calculated that 2% hoop strain corresponded to 150 psig, including the effects of strain hardening of the rebar. At this level of strain, he concluded that liner tear is certain at discontinuities such as around penetrations and stiffener plates. Further, concrete cracking at 2% general strain will have removed much of the liner support. At 2% strain, the cylinder wall has moved out 16 in.

Results of Expert A's Elicitation

Expert A provided the following table, which contains his views on failure probability and mode of failure:

Pressure (psig)	Cumulative Fail. Probability	Conditional Probability Leak	Rupture	Cat. Rupture
119	0.001	1.0	0.0	0.0
127	0.25	0.7	0.3	0.0
135	0.50	0.5	0.5	0.0
142	0.75	0.4	0.5	0.1
150	1.0	0.2	0.3	0.5
170	1.0	0.0	0.0	1.0

Interpolation was used to create Table A-1 (see page 5.2-3), which gives the probabilities for increments of 5 psig. The cumulative failure curve is essentially linear from 120 psig to 150 psig, and Expert A thought that this was a good representation of his conclusions.

If the leak that develops is not sufficiently large to arrest the pressure rise, Expert A thought that the liner tear would increase in size, either in length or width of both, until the opening was large enough to arrest the pressure rise. He was certain that it would not go to a CR once a leak had developed. CR occurs, then, only in the very few cases where the pressure has reached the 145 to 150 psig range without a leak developing.

REFERENCES

A-1. United Engineers & Constructors, "Indian Point Units 2 and 3, Containment Capability Analysis," prepared in support of the Indian Point Probabilistic Safety Study, Philadelphia, PA, March 1980.

A-2. W. J. Pananos and C. F. Reeves, "Containment Integrity at Surry Nuclear Power Station," TP84-13, Stone & Webster Engineering Corp., Boston, MA, 1984.

Expert B's Elicitation

Containment Failure at Surry

Description of Expert B's Rationale/Methodology

Expert B based his analysis on the Stone & Webster study of the Surry containment,[B-1] studies of other plants such as Indian Point 2 and 3,[B-2] Seabrook,[B-3] and the 1/6th-scale test at Sandia.[B-4] Temperatures and pressure rise times are such that all the cases can be considered together. The expected leakage modes are small liner tears, hatch ovalization, and penetration failures. The expected rupture modes are large liner tears, hatch failure, and penetration failures. The expected burst or catastrophic rupture failure mode is complete hoop failure of the rebar.

Expert B's hoop membrane stress analysis showed the following:

Pressure (psig)	σ_m (ksi)	Condition
120	57.0	Shell general yield, rebar yield
130	62.5	Cadweld minimum
144	70.0	Minimum rebar failure
166	82.0	Average rebar failure

Results of Expert B's Elicitation

Expert B placed the lower bound of any type of failure at 75 psig. While the bulk of the failure probability falls above 90 psig, some probability has been placed below 90 psig to account for possible construction defects, such as poor cadwelds of the rebar. Other sources of uncertainty are the rebar placement in the apex of the dome, the hoop bars in the dome, and the reinforcing around the equipment hatch. Failure could be expected to result from localized strain in the rebars, which leads to liner tears. As with the other panel members, he expects failures at low pressures to be mostly leaks due to defects, liner tears, and such. In the middle of the failure pressure range ruptures predominate, and CR or burst failures occur only for the upper end of the range.

Expert B provided the following table, which contains his views on failure probability and mode of failure:

Pressure (psig)	Cumulative Fail. Probability	Conditional Probability Leak	Rupture	Cat. Rupture
75	0.01	0.95	0.05	0.00
90	0.05	0.80	0.20	0.00
105	0.25	0.70	0.30	0.00
120	0.50	0.60	0.40	0.00
135	0.85	0.10	0.80	0.10
150	0.99	0.05	0.65	0.30
165	1.00	0.00	0.20	0.80

Expert B allowed for the possibility of leaks as low as 75 psig because he considered the possibility that some of the rebar cadwelds might not have produced the proper strength and because of the reinforcing details around some of the larger openings. Either of these might lead to localized stress concentrations which would result in liner tears at relatively low pressures. Expert B thus placed half his probability of failure below 120 psig where shell and rebar general yield occur. He pointed out that the Surry containment was constructed quite some time ago when construction methods and quality control were not at today's standards. The failures below 120 psig are all leaks or large leaks (ruptures). Expert B does not think that catastrophic rupture is likely unless the containment fails at pressures considerably in excess of 120 psig.

The pressure range from 105 to 135 psig contains 60% of the failure probability. Interpolation was used to generate intermediate values from the table above so that Table B-1 (see page 5.2-4), in 5 psig increments, could be constructed.

REFERENCES

B-1. W. J. Pananos and C. F. Reeves, "Containment Integrity at Surry Nuclear Power Station," TP84-13, Stone & Webster Engineering Corp., Boston, MA, 1984.

B-2. United Engineers & Constructors, "Indian Point Units 2 and 3, Containment Capability Analysis," prepared in support of the Indian Point Probabilistic Safety Study, Philadelphia, PA, March 1980.

B-3. United Engineers & Constructors, "Containment Ultimate Capacity of Seabrook Station Units 1 & 2 for Internal Pressure Loads," Philadelphia, PA, February 1983.

B-4. D. S. Horschel, Sandia National Laboratories, Letter to J. F. Costello, U.S. Nuclear Regulatory Commission, August 2, 1987.

Expert C's Elicitation

Containment Failure at Surry

Description of Expert C's Rationale/Methodology

Expert C based his conclusions on an analysis of the mid-section of the cylindrical portion of the containment. His study of the drawings and the results of other analyses led him to conclude that this was the weakest portion of the containment. Much of his conclusions about the leak mode and liner tear come from the 1/6th-scale model test at Sandia.[C-1] As with the others considering this issue, Expert C concluded that the cases were indistinguishable; the pressure rises were slow enough that all the loading was static, and the temperatures were well below those at which degradation of structural properties occurs.

Development of either a leak or a rupture precludes the later occurrence of CR. Once a liner tear has developed, it is difficult to see how it could be kept from expanding with a continued increase in pressure. Further, additional liner tears may develop elsewhere. Distinguishing between leak and rupture is difficult because there is a continuum of sizes, and a leak may develop into a rupture as the tear increases in size. On the whole, CR is quite unlikely. Leaks are more likely than rupture at the lower failure pressures, and vice versa at the higher pressures.

Results of Expert C's Elicitation

Expert C provided a table for the failure probability and mode of failure for six pressure ranges. This table provides the probability (density) of failure and the joint probability for the three failure modes and takes into account Expert C's uncertainty about the actual rebar properties.

Pressure (psig)	Failure Probability Density	Joint Probability: Leak	Cat. Rupture	Rupture
120 to 135	0.10	0.07	0.03	0.00
135 to 140	0.30	0.18	0.12	0.00
140 to 147	0.40	0.16	0.20	0.04
147 to 155	0.15	0.03	0.05	0.07
155 to 164	0.04	0.00	0.01	0.03
164 to 208	0.01	0.00	0.00	0.01

The marginal probabilities of failure are 44% leak, 41% rupture, and 15% CR. Interpolation was used to expand this table to one with 5 psig increments. The results are shown in Table C-1 (see page 5.2-5).

Expert C was fairly confident that failure could be expected between 135 psig and 155 psig as 85% of his probability lay within that range. Forty percent of the probability lay within the 140 to 147 psig range. Within the range where failure was most likely to occur, leak and rupture were approximately equally likely. The distribution was terminated at 200 psig, since the 99% value for the pressure rise did not exceed 200 psig in any of the cases considered by the Containment Loads Panel.

REFERENCE

C-1. D. S. Horschel, Sandia National Laboratories, Letter to J. F. Costello, U.S. Nuclear Regulatory Commission, August 2, 1987.

Expert D's Elicitation

Containment Failure at Surry

Description of Expert D's Rationale/Methodology

Expert D's analysis led him to conclude that a leak was certain to develop by 130 psig. At this pressure the rebar has yielded considerably and reached a strain of about 1%. He would expect leaks to develop due to dislocation at discontinuities.[D-1] There is no possibility of a leak developing at pressures below 75 psig. This value was obtained by hoop membrane stress analysis assuming that the liner is at its yield stress of 35 ksi. If the liner and the hoop reinforcement are both at their respective yield stress, which is 55 ksi for the reinforcement and 35 ksi for the liner, the pressure would be 110 psig. Expert D took 110 psig to be his median value for leaks. He noted that the specified minimum yield strength is 55 ksi for the reinforcement and 35 ksi for the liner.

Expert D took the lower threshold for rupture to be 140 psig, which was determined by a local effects analysis of the discontinuity at the basemat-cylinder junction.[D-2] He expected that a crack would open at this junction for a substantial portion of the circumference. Although the crack might be very small, it would be long enough to depressurize the containment in less than 2 hours. He concluded that rupture was certain when the main reinforcement reaches its specified minimum ultimate strength. For the Surry containment, Expert D considered catastrophic rupture to be impossible.

Results of Expert D's Elicitation

Expert D provided separate distributions for leak and for rupture. The leak distribution is.

Pressure (psig)	75	80	85	90	95	100	105	110	115	120	125	130
Cum. Distrib. Fn.	0.0	.02	.05	.075	.125	.20	.30	.50	.85	.95	.98	1.0

This distribution has 75% of the leakage failure between 100 and 120 psig.

The rupture distribution is:

Pressure (psig)	140	145	150	155	160	165	170
Cum. Distrib. Fn.	0.0	.05	.20	.50	.80	.95	1.0

This distribution has 60% of the rupture failures between 150 and 160 psig.

These independent distributions for leak and rupture were used directly in Table D-1 (see page 5.2-6). The distributions for the leak and rupture modes do not overlap. Leakage modes occur below 130 psig and rupture mode occur above 140 psig. The region with no failures between the two modes, from 130 psig to 140 psig, is due to strain hardening. In other words, if failure does not occur during rebar general yield, then strain hardening will put off failure until about 155 psig.

Expert D was confident that a leak would develop by 130 psig and that ruptures would occur only above 140 psig. If the development of a leak did not arrest the pressure rise, then Expert D concluded that the hole size would increase, changing the failure mode from leak to rupture.

REFERENCES

D-1. Y. R. Rashid et al., "State-of-the-Art Review of Concrete Containment Response to Severe Overpressurization," Transactions of the 9th SMIRT Conference, Lausanne, Switzerland, August 17-21, 1987.

D-2. R. A. Dameron et al., "Analytical Correlation and Post-Test Analysis of the Sandia 1:6-Scale Reinforced Concrete Containment Test," Fourth Workshop on Containment Integrity, Arlington, VA, June 14-17, 1988.

5.3 Issue 3. Peach Bottom Containment Failure

Experts consulted: David Clauss, Sandia National Laboratories; Kam Mohktarian, Chicago Bridge & Iron NA-CON, Inc.; Joe Rashid, ANATECH Research Corporation

Issue Description

What are the plausible pressure-temperature induced containment failure modes at Peach Bottom? For the identified containment failure modes and for each pressure-temperature loading case, at what pressure would the Peach Bottom containment fail?

The following sections on Background, Discussion, and Context are reprinted as they were presented to the Structural Response Expert Panel.

Background

Peach Bottom has a GE Mark I pressure suppression containment with a design pressure of 62 psig. The Reactor Safety Study (RSS)[3-1] analysis of the Peach Bottom containment predicted failure in the torus with a mean failure pressure of 160 psig. Many later studies of Peach Bottom have referenced the Ames Laboratory study[3-2] which predicted that the Mark I containment at Browns Ferry would fail at the drywell knuckle (junction between the cylindrical and spherical sections) at 117 psig based on a 0.2% strain criterion. Browns Ferry has a thicker, more uniform torus shell than Peach Bottom. The recently completed Chicago Bridge and Iron (CB&I) study[3-3] addressed global containment shell failure for a Mark I containment essentially identical to that at Peach Bottom Unit 2. CB&I found the first point on the containment to reach 1% membrane strain (failure criterion) was on the upper portion of the torus at 159 psig. CB&I recommended further study of penetrations, personnel lock, equipment hatch, and drywell head closure bolts to address the potential for local failure. IDCOR has postulated creep failure of the drywell shell in scenarios involving core concrete interactions (CCI) that result in drywell temperatures approaching 1200°F.

Four loading cases are:

Case 1: The containment is being gradually pressurized. Drywell shell temperatures are less than 500°F. This may occur either before vessel breach or, given water-cooled debris, after vessel breach. No containment leak has yet developed.

Case 2: At the time of vessel breach, the containment is rapidly pressurized from a pressure P_{bf} to a peak pressure P_{pk}.

P_{bf} is in the 60 to 120 psig range. Drywell shell temperatures are < 500°F during the pressurization. No containment leak exists before vessel breach.

Case 3 The containment is being gradually pressurized at high temperatures (800 to 1200°F) as a result of sustained CCI after vessel breach. No containment leak has yet developed.

Case 4 The containment at low (near atmospheric) pressure as gases from sustained CCI are vented through the suppression pool via a wetwell leak or rupture; however, the temperature of the drywell shell is increasing into the high temperature (800 to 1200°F) regime.

Ten failure modes and locations were identified by the experts.

1. WWLaW--wetwell leak above water line with no bypass;
2. WWLbW--wetwell leak below water line with bypass;
3. WWRaW--wetwell rupture above water line with no bypass;
4. WWRbW--wetwell rupture below water line with bypass;
5. CWWR--catastrophic wetwell rupture;
6. DWL--drywell leak to reactor building;
7. DWR--drywell rupture to reactor building;
8. DWHL--drywell head leak to refueling floor;
9. DWHR--drywell head rupture to refueling floor;
10. CDWR--catastrophic drywell rupture to reactor building.

Discussion

The results will be used in the Accident Progression Event Tree (APET) in the following way.

1. Question: For this time period did containment fail? For each observation in the sample, the sampling program will select a load pressure from the containment load distribution; then it will select a failure pressure from the appropriate containment failure pressure distribution. If the failure pressure is less than the containment load pressure, then failure occurs with 1.0 probability for that observation.

2. Question: What is the containment failure mode and location? For this question, there are two ways to reach the load pressure: (1) a slow pressure rise, and (2) a fast pressure rise. For the slow pressure rise, the sampling program will select a random number between zero and one for each observation. The user function will compare this number to the ordered sum of the conditional failure mode probabilities for the failure pressure selected in the previous question. The failure mode corresponding to the increment

that the random number falls in will be chosen for that observation. For fast pressure rise, only a rupture or catastrophic rupture will preclude further pressure rise. The user function calculates the conditional probability of the various modes over the interval between the selected failure and load pressures. This is done in the user function in the APET for each observation. The resulting conditional probabilities will be compared to a random number as in the slow case and a failure mode selected for that observation.

Accident Progression Event Tree Context

A wide spectrum of failure sizes is conceivable, ranging from very small leaks to large ruptures. Induced leaks that are too small to preclude further pressurization are considered; however, because such small leaks would not appreciably alter the accident progression or preclude larger leaks or rupture, small induced leaks are not very significant to risk. Consequently, the focus of this issue is to identify alternative modes for larger leaks or ruptures, with the terms leak and rupture defined as follows:

> A <u>leak</u> is an opening that would arrest a gradual containment pressure buildup but would not result in containment depressurization within 2 h. A gradual pressure buildup means a few psi per hour and excludes pressure spikes arising from rapid reactor coolant system's depressurization, combustion events, steam spikes, and direct containment heating. In the NUREG-1150 analysis for Peach Bottom, openings of size 10 in.^{2} to 1.8 ft^2 are classified as leaks.
>
> A <u>rupture</u> is an opening that would result in rapid (<2 h) containment depressurization. For Peach Bottom, openings in excess of 1.8 ft^2 are classified as ruptures.

The review group is specifically requested to consider a <u>catastrophic rupture</u> that would eliminate major portions of the containment structures (e.g., 1:8th-scale steel model) as a potential failure mode.

Based on differences in the decontamination potential for radionuclide releases, the Peach Bottom APET distinguishes four location categories for containment failure:

Cat. 1 Failure in the torus that does not lead to suppression pool bypass (e.g., an opening in the top of the torus);

Cat. 2 Failure in the torus that leads to suppression pool bypass (i.e., to draining of the suppression pool);

Cat. 3 Failure in the drywell resulting in flow to the reactor building (e.g., failure in a downcomer);

Cat. 4 Failure in the drywell resulting in flow to the refueling bay (e.g., drywell head seal leakage).

The review group may, of course, identify more than one mode of failure corresponding to any of these broad location categories; however, from a source term perspective at least this level of delineation is required.

Pressure-temperature-induced containment failure questions are asked in the Peach Bottom APET for four different time regimes: (1) before uncovering the core, (2) before reactor pressure vessel breach when the containment pressure buildup is fairly steady as steam and hydrogen are released from the reactor vessel to containment, (3) immediately after reactor vessel breach when a rapid containment pressure increase is possible particularly in high-pressure meltdown scenarios, and (4) later, when a steady buildup in containment pressure is possible given either water-cooled debris or CCIs. In the presence of sustained CCIs, the containment temperature will also increase steadily.

Based on severe-accident pressure and temperature loadings calculations performed using codes such as MARCH, MAAP, MELCOR, and CONTAIN, drywell temperatures may be divided into the following two categories for the purpose of assessing containment failure modes:

Med. T Drywell structure temperatures are less than 500°F as would be the case before or immediately after vessel breach.

High T Drywell structural temperatures are in the 800°F to 1200°F range. This case is only possible after vessel failure, with uncooled core debris on the drywell floor.

Summary of Results

Table 3-1 shows the aggregate results for cases 1 and 2. Table 3-2 lists results used in the accident frequency analysis. Tables 3-3 and 3-4 contain the aggregate results for case 3. Table 3-3 applies when the drywell is at 800°F and Table 3-4 applies when the drywell is at 1200°F. The results for case 4 are given in Table 3-5.

The aggregate results of this issue are also used in the accident frequency analysis of NUREG-1150. For certain sequences in which core cooling is still working but where containment heat removal has failed, the containment pressure will continue to rise until failure occurs. In this case, failure is certain, but we need to know if a leak or rupture has occurred and if the fission products escape to the reactor building or to the refueling floor.

The results of the slow pressure rise case (case 1) are used in the accident frequency analysis. The sum over all leaks and all ruptures at the failure pressure selected for locations in the reactor building and the refueling floor gives the conditional probability of leak versus rupture and location. For the point estimate calculation the mean values are used. For the LHS TEMAC runs, the cumulative failure distribution is sampled to select a failure pressure and then the conditional probability for that failure pressure for leak versus rupture is used to quantify the events for that observation.

Method of Aggregation

For each of the cases, the experts assessed failure probabilities over slightly different ranges and their values had to be extrapolated both above and below their assessed range. In the lower direction, a failure probability of zero was assigned since these pressures were below the experts' lowest failure pressure. The conditional probability of the various modes was assigned the same value as those at the experts' lowest assessed pressure. In the upper direction, the experts' curves were extended as described in each case.

For the aggregation of the experts' results in this situation, we need two different pieces of data. First, we need to determine the failure pressure and, second, the conditional probability of each failure mode. Each expert's results were used to calculate a cumulative probability of failure curve. The aggregated cumulative failure probability was calculated by simple averaging:

$$PT(ave,i)=(p(1,i)+p(2,i)+p(3,i))/3$$

where $p(j,i)$ = the jth experts' cumulative probability of failure at pressure i and $PT(ave,i)$ = the aggregate cumulative probability of failure at pressure i.

The experts' results were then converted into the form of conditional probabilities of the mth failure mode at a certain pressure i. The aggregated conditional probability of the mth mode at pressure i was calculated by simple averaging:

$$c(ave,i,m) = (c(1,i,m) + c(2,i,m) + c(3,i,m)) / 3$$

where $c(ave,i,m)$ = the aggregate conditional probability of the mth mode at pressure i, and $c(j,i,m)$ = the conditional probability of failure of the mth mode for the jth expert at pressure i, with the following exception: for pressures where the cumulative probability of failure is zero, the conditional failure mode probabilities are set equal to those for the lowest pressure for which the cumulative failure probability is non-zero.

Table 3-1
Average of Experts: Cases 1 and 2

Pressure (psig)	Cumulative Probability	Conditional Probability of Failure in Mode I at Pressure J: WWLaW	WWLbW	WWRaW	WWRbW	CWWR	DWL	DWHL	DWR	DWPS	CDVR
90.0000	0.0000	0.2778	0.0000	0.1111	0.0000	0.0000	0.0556	0.5556	0.0000	0.0000	0.0000
95.0000	0.0050	0.2778	0.0000	0.1111	0.0000	0.0000	0.0556	0.5556	0.0000	0.0000	0.0000
100.0000	0.0100	0.2778	0.0000	0.1111	0.0000	0.0000	0.0556	0.5556	0.0000	0.0000	0.0000
105.0000	0.0183	0.2778	0.0000	0.1111	0.0000	0.0000	0.0556	0.5556	0.0000	0.0000	0.0000
110.0000	0.0242	0.2778	0.0000	0.1111	0.0000	0.0000	0.0556	0.5556	0.0000	0.0000	0.0000
115.0000	0.0357	0.2712	0.0078	0.0967	0.0078	0.0078	0.0484	0.5523	0.0039	0.0039	0.0000
120.0000	0.0471	0.2647	0.0157	0.0823	0.0157	0.0157	0.0412	0.5491	0.0078	0.0078	0.0000
125.0000	0.0751	0.2582	0.0235	0.0680	0.0235	0.0235	0.0340	0.5457	0.0118	0.0118	0.0000
130.0000	0.1095	0.2931	0.0360	0.0536	[illegible]	0.0314	0.0268	0.4864	0.0157	0.0157	0.0000
135.0000	0.1556	0.4639	0.0474	0.0392	[illegible]	0.0392	0.0196	0.3722	0.0196	0.0196	0.0000
140.0000	0.2220	0.3486	0.0384	0.0422	[illegible]	0.0500	0.0203	0.4267	0.0172	0.0172	0.0000
145.0000	0.3919	0.5755	0.0567	0.0677	[illegible]	0.0608	0.0211	0.1595	0.0149	0.0149	0.0000
150.0000	0.5703	0.6124	0.0562	[illegible]	[illegible]	0.0715	0.0218	0.0971	0.0125	0.0125	0.0000
155.0000	0.6628	0.4671	0.0408	0.0877	0.0961	0.0823	0.0225	0.1105	0.0829	0.0101	0.0000
160.0000	0.7539	0.3422	0.0309	[illegible]	0.1146	0.0930	0.0233	0.1816	0.0570	0.0077	0.0000
165.0000	0.8317	0.0876	0.0317	0.3329	0.1783	0.0925	0.0612	0.1381	0.0631	0.0067	0.0029
170.0000	0.9247	0.0665	0.0318	0.2678	0.2706	0.0920	0.0941	0.1408	0.0250	0.0057	0.0058
175.0000	0.9616	0.0558	0.0259	0.2571	0.2667	0.1074	0.0913	0.1319	0.0460	0.0116	0.0064
180.0000	0.9964	0.0515	0.0207	0.2711	0.3211	0.1228	0.0645	0.0925	0.0312	0.0175	0.0070
185.0000	0.9976	0.0301	0.0179	0.0414	0.1865	0.1241	[illegible]	0.2434	0.1284	0.0172	0.0069
190.0000	0.9987	0.0300	0.0177	0.0407	0.2166	0.1254	0.1889	0.2077	0.1492	0.0170	0.0068
195.0000	0.9998	0.0309	0.0175	0.0400	0.2639	0.1267	0.1822	0.2308	0.0847	0.0167	0.0067
200.0000	0.9999	0.0287	0.0173	0.0400	0.2420	0.1267	0.1649	0.2897	0.0573	0.0167	0.0067
205.0000	0.9999	0.0293	0.0174	0.0400	0.1120	0.1267	0.0200	0.4063	0.2251	0.0167	0.0067
210.0000	0.9999	0.0285	0.0173	0.0400	0.1092	0.1267	0.0200	0.4225	0.2127	0.0167	0.0067
215.0000	0.9999	0.0287	0.0174	0.0400	0.1412	0.1267	0.0200	0.4385	0.1632	0.0167	0.0067
220.0000	1.0000	0.0305	0.0175	0.0400	0.1740	0.1267	0.0200	0.3965	0.1715	0.0167	0.0067
225.0000	1.0000	0.0269	0.0171	0.0400	0.1095	0.1267	0.0200	0.3637	0.2728	0.0167	0.0067
230.0000	1.0000	0.0267	0.0171	0.0400	0.1183	0.1267	0.0200	0.3300	0.2980	0.0167	0.0067
235.0000	1.0000	0.0261	0.0172	0.0400	0.1856	0.1267	0.0200	0.2990	0.2601	0.0167	0.0067
240.0000	1.0000	0.0273	0.0171	0.0400	0.1952	0.1267	0.0200	0.2947	0.2556	0.0167	0.0067
245.0000	1.0000	0.0261	0.0170	0.0400	0.1839	0.1267	0.0200	0.2788	0.2842	0.0167	0.0067
250.0000	1.0000	0.0253	0.0169	0.0400	0.1987	0.1267	0.0200	0.2706	0.2785	0.0167	0.0067
255.0000	1.0000	0.0245	0.0168	0.0400	0.2239	0.1267	0.0200	0.2582	0.2666	0.0167	0.0067
260.0000	1.0000	0.0233	0.0167	0.0400	0.2529	0.1267	0.0200	0.2504	0.2467	0.0167	0.0067
265.0000	1.0000	0.0233	0.0167	0.0400	0.0223	0.1267	0.0200	0.3134	0.4132	0.0167	0.0067
270.0000	1.0000	0.0233	0.0167	0.0400	0.0233	0.1267	0.0200	0.3467	0.3800	0.0167	0.0067
275.0000	1.0000	0.0233	0.0167	0.0400	0.0233	0.1267	0.0200	0.5467	0.1800	0.0167	0.0067

Table [illegible]

Peach Bottom Front-End [illegible] [illegible]ases 1 and 2

Pressure (psig)	Cumulative Probability	Conditional Probability of Failure at Pressure J					
		Leak	LtRF	LtRB	Rupture	RtRF	RtRB
90.0000	0.0000	0.8889	0.5556	0.3333	0.1111	0.0000	0.1111
95.0000	0.0050	0.8889	0.5556	0.3333	0.1111	0.0000	0.1111
100.0000	0.0100	0.8889	0.5556	0.3333	0.1111	0.0000	0.1111
105.0000	0.0183	0.8889	0.5556	0.3333	0.1111	0.0000	0.1111
110.0000	0.0242	0.8889	0.5556	0.3333	0.1111	0.0000	0.1111
115.0000	0.0357	0.8797	0.5523	0.3274	0.1203	0.0039	0.1163
120.0000	0.0471	0.8706	0.5491	0.3215	0.1294	0.0078	0.1216
125.0000	0.0751	0.8614	0.5457	0.3157	0.1386	0.0118	0.1268
130.0000	0.1095	0.8523	0.4964	0.3559	0.1477	0.0157	0.1320
135.0000	0.1556	0.8431	0.3722	0.4709	0.1569	0.0196	0.1373
140.0000	0.2220	.8342	0.4267	0.4075	0.1658	0.0172	0.1486
145.0000	0.3919	0.8128	0.1595	0.6533	0.1872	0.0149	0.1723
150.0000	0.5703	0.7875	0.0971	0.6904	0.2125	0.0125	0.2000
155.0000	0.6628	0.6409	0.1105	0.5304	0.3591	0.0101	0.3490
160.0000	0.7539	0.5779	0.1816	0.3963	0.4221	0.0077	0.4144
165.0000	0.8317	0.3236	0.1381	0.1855	0.6764	0.0067	0.6697
170.0000	0.9247	0.3332	0.1408	0.1924	0.6668	0.0057	0.6611
175.0000	0.9616	0.3048	0.1319	0.1730	0.6952	0.0116	0.6835
180.0000	0.9964	0.2292	0.0925	0.1367	0.7708	0.0175	0.7532
185.0000	0.9976	0.4955	0.2434	0.2521	0.5045	0.0172	0.4873
190.0000	0.9987	0.4444	0.2077	0.2366	0.5556	0.0170	0.5387
195.0000	0.9998	0.4614	0.2308	0.2306	0.5386	0.0167	0.5219
200.0000	0.9999	0.5007	0.2897	0.2110	0.4993	0.0167	0.4827
205.0000	0.9999	0.4729	0.4063	0.0666	0.5271	0.0167	0.5105

Table 3-2 (continued)

Pressure (psig)	Cumulative Probability	Conditional Probability of Failure at Pressure J					
		Leak	LtRF	LtRB	Rupture	RtRF	RtRB
210.0000	0.9999	0.4881	0.4223	0.0658	0.5119	0.0167	0.4952
215.0000	0.9999	0.5056	0.4385	0.0671	0.4944	0.0167	0.4777
220.0000	1.0000	0.4645	0.3965	0.0680	0.5355	0.0167	0.5188
225.0000	1.0000	0.4277	0.3637	0.0640	0.5723	0.0167	0.5556
230.0000	1.0000	0.3937	0.3300	0.0637	0.6063	0.0167	0.5896
235.0000	1.0000	0.3643	0.2990	0.0653	0.6357	0.0167	0.6190
240.0000	1.0000	0.3592	0.2947	0.0644	0.6408	0.0167	0.6242
245.0000	1.0000	0.3419	0.2788	0.0631	0.6581	0.0167	0.6414
250.0000	1.0000	0.3329	0.2706	0.0622	0.6671	0.0167	0.6505
255.0000	1.0000	0.3195	0.2582	0.0613	0.6805	0.0167	0.6639
260.0000	1.0000	0.3104	0.2504	0.0600	0.6896	0.0167	0.6730
265.0000	1.0000	0.3734	0.3134	0.0600	0.6266	0.0167	0.6099
270.0000	1.0000	0.4067	0.3467	0.0600	0.5933	0.0167	0.5767
275.0000	1.0000	0.6067	0.5467	0.0600	0.3933	0.0167	0.3767

Table 3-3
Average of Experts: Case 3A

Pressure (psig)	Cumulative Probability	Conditional Probability of Failure in Mode I at Pressure J									
		WWLaW	WWLbW	WWRaW	WWRbW	CWWR	DWL	DWWL	DWR	DWWR	CDWR
50.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1111	0.8889	0.0000	0.0000	0.0000
55.0000	0.0033	0.0000	0.0000	0.0000	0.0000	0.0000	0.1111	0.8889	0.0000	0.0000	0.0000
60.0000	0.0100	0.0000	0.0000	0.0000	0.0000	0.0000	0.1111	0.8889	0.0000	0.0000	0.0000
65.0000	0.0187	0.0000	0.0000	0.0000	0.0000	0.0000	0.1111	0.8889	0.0000	0.0000	0.0000
70.0000	0.0300	0.0000	0.0000	0.0000	0.0000	0.0000	0.1111	0.8889	0.0000	0.0000	0.0000
75.0000	0.0483	0.0000	0.0000	0.0000	0.0000	0.0000	0.1111	0.8889	0.0000	0.0000	0.0000
80.0000	0.0658	0.0000	0.0000	0.0000	0.0000	0.0000	0.1111	0.8889	0.0000	0.0000	0.0000
85.0000	0.0950	0.0000	0.0000	0.0000	0.0000	0.0000	0.1111	0.8889	0.0000	0.0000	0.0000
90.0000	0.1208	0.0000	0.0000	0.0000	0.0000	0.0000	0.1111	0.8889	0.0000	0.0000	0.0000
95.0000	0.1517	0.0000	0.0000	0.0000	0.0000	0.0000	0.1111	0.8889	0.0000	0.0000	0.0000
100.0000	0.1964	0.0139	0.0069	0.0139	0.0000	0.0000	0.0972	0.8681	0.0000	0.0000	0.0000
105.0000	0.2411	0.0278	0.0139	0.0278	0.0000	0.0000	0.0833	0.8472	0.0000	0.0000	0.0000
110.0000	0.3069	0.0417	0.0208	0.0417	0.0000	0.0000	0.0694	0.5957	0.2307	0.0000	0.0000
115.0000	0.3655	0.0556	0.0278	0.0556	0.0000	0.0000	0.0556	0.5129	0.2926	0.0000	0.0000
120.0000	0.4501	0.0529	0.0253	0.0484	0.0068	0.0203	0.0507	0.5897	0.2036	0.0023	0.0000
125.0000	0.5378	0.0731	0.0229	0.0413	0.6135	0.0405	0.1405	0.5863	0.0774	0.0045	0.0000
130.0000	0.6178	0.0665	0.0205	0.0342	0.0203	0.0608	0.1263	0.5994	0.0744	0.0068	0.0000
135.0000	0.6819	0.1003	0.0180	0.0270	0.0270	0.0811	0.1751	0.4748	0.0877	0.0090	0.0000
140.0000	0.7750	0.0990	0.0170	0.0250	0.0227	0.0693	0.1721	0.4790	0.0666	0.0481	0.0012
145.0000	0.8682	0.2455	0.0276	0.0245	0.0242	0.0574	0.1946	0.2799	0.0574	0.0872	0.0023
150.0000	0.9465	0.2548	0.0240	0.0240	0.0258	0.0456	0.1475	0.2620	0.0565	0.1263	0.0035
155.0000	0.9544	0.2582	0.0208	0.0265	0.0553	0.0460	0.1639	0.2463	0.0521	0.1264	0.0035
160.0000	0.9798	0.2263	0.0168	0.0282	0.0791	0.0463	0.1651	0.2639	0.0444	0.1265	0.0034
165.0000	0.9903	0.0579	0.0144	0.0327	0.1267	0.0467	0.0167	0.5311	0.0439	0.1267	0.0033
170.0000	0.9985	0.0420	0.0126	0.0310	0.2207	0.0467	0.0167	0.4746	0.0263	0.1267	0.0033
175.0000	0.9996	0.0336	0.0116	0.0234	0.1456	0.0467	0.0167	0.5547	0.0377	0.1267	0.0033
180.0000	1.0000	0.0422	0.0125	0.0200	0.2338	0.0467	0.0167	0.4673	0.0308	0.1267	0.0033
185.0000	1.0000	0.0235	0.0104	0.0200	0.0506	0.0467	0.0167	0.6184	0.0838	0.1267	0.0033
190.0000	1.0000	0.0263	0.0107	0.0200	0.0865	0.0467	0.0167	0.5096	0.1535	0.1267	0.0033
195.0000	1.0000	0.0208	0.0101	0.0200	0.0247	0.0467	0.0167	0.6921	0.0389	0.1257	0.0033
200.0000	1.0000	0.0277	0.0109	0.0200	0.1187	0.0467	0.0167	0.3933	0.2360	0.1267	0.0033
205.0000	1.0000	0.0258	0.0107	0.0200	0.1006	0.0467	0.0167	0.3933	0.2562	0.1267	0.0033
210.0000	1.0000	0.0247	0.0105	0.0200	0.0914	0.0467	0.0167	0.3933	0.2667	0.1267	0.0033
215.0000	1.0000	0.0235	0.0104	0.0200	0.0788	0.0467	0.0167	0.3933	0.2806	0.1267	0.0033
220.0000	1.0000	0.0223	0.0103	0.0200	0.0606	0.0467	0.0167	0.3933	0.3000	0.1267	0.0033
225.0000	1.0000	0.0209	0.0101	0.0200	0.0346	0.0467	0.0167	0.3933	0.3278	0.1267	0.0033

Table 3-4
Average of Experts: Case 3B

Pressure (psig)	Cumulative Probability	Conditional Probability of Failure in Mode I at Pressure J									
		WWLaW	WWLbW	WWRaW	WWRbW	CWWR	DWL	DWHL	DWR	DWHR	CDWR
5.0000	0.0167	0.0000	0.0000	0.0000	0.0000	0.0000	0.3467	0.6533	0.0000	0.0000	0.0000
10.0000	0.1667	0.0000	0.0000	0.0000	0.0000	0.0000	0.3467	0.6533	0.0000	0.0000	0.0000
15.0000	0.3333	0.0000	0.0000	0.0000	0.0000	0.0000	0.3467	0.6533	0.0000	0.0000	0.0000
20.0000	0.3333	0.0000	0.0000	0.0000	0.0000	0.0000	0.3467	0.6533	0.0000	0.0000	0.0000
25.0000	0.3333	0.0000	0.0000	0.0000	0.0000	0.0000	0.3467	0.6533	0.0000	0.0000	0.0000
30.0000	0.3611	0.0000	0.0000	0.0000	0.0000	0.0000	0.3467	0.6533	0.0000	0.0000	0.0000
35.0000	0.3889	0.0000	0.0000	0.0000	0.0000	0.0000	0.3467	0.6533	0.0000	0.0000	0.0000
40.0000	0.4167	0.0000	0.0000	0.0000	0.0000	0.0000	0.3467	0.6533	0.0000	0.0000	0.0000
45.0000	0.4942	0.0000	0.0000	0.0000	0.0000	0.0000	0.3615	0.5686	0.0081	0.0618	0.0000
50.0000	0.5817	0.0000	0.0000	0.0000	0.0000	0.0000	0.3763	0.4839	0.0161	0.1237	0.0000
55.0000	0.6805	0.0000	0.0000	0.0000	0.0000	0.0000	0.3677	0.4364	0.0172	0.1716	0.0069
60.0000	0.7725	0.0000	0.0000	0.0000	0.0000	0.0000	0.3667	0.1469	0.3064	0.1733	0.0067
65.0000	0.9022	0.0000	0.0000	0.0000	0.0000	0.0000	0.3667	0.1173	0.3361	0.1733	0.0067
70.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3667	0.1072	0.3482	0.1733	0.0067
75.0000	1.0000	0.0000	0.0000	0.0030	0.0000	0.0000	0.3667	0.4367	0.0167	0.1733	0.0067
80.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3667	0.4367	0.0167	0.1733	0.0067
85.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3667	0.4367	0.0167	0.1733	0.0067
90.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3667	0.4367	0.0167	0.1733	0.0067
95.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3667	0.4367	0.0167	0.1733	0.0067
100.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3667	0.4367	0.0167	0.1733	0.0067
105.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3667	0.4133	0.0167	0.1967	0.0067
110.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3667	0.3833	0.0167	0.2267	0.0067
115.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3667	0.3700	0.0167	0.2400	0.0067
120.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3667	0.2200	0.0167	0.3900	0.0067
125.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3667	0.3133	0.0167	0.2967	0.0067
130.0000	1.0000	0.0037	0.0004	0.0000	0.0000	0.0000	0.3667	0.2252	0.0167	0.3808	0.0067
135.0000	1.0000	0.0022	0.0002	0.0000	0.0000	0.0000	0.3667	0.1794	0.0167	0.4282	0.0067
140.0000	1.0000	0.0015	0.0002	0.0000	0.0000	0.0000	0.3667	0.1398	0.0167	0.4685	0.0067
145.0000	1.0000	0.0385	0.0043	0.0005	0.0018	0.0000	0.3667	0.1177	0.0167	0.4472	0.0067
150.0000	1.0000	0.0208	0.0024	0.0005	0.0021	0.0000	0.3667	0.1033	0.0167	0.4809	0.0067
155.0000	1.0000	0.2047	0.0232	0.0128	0.0925	0.0000	0.3667	0.1033	0.0167	0.1733	0.0067
160.0000	1.0000	0.1399	0.0159	0.0190	0.1585	0.0000	0.3667	0.1033	0.0167	0.1733	0.0067
165.0000	1.0000	0.0750	0.0086	0.0252	0.2244	0.0000	0.3667	0.1033	0.0167	0.1733	0.0067
170.0000	1.0000	0.0301	0.0036	0.0151	0.2846	0.0000	0.3667	0.1033	0.0167	0.1733	0.0067
175.0000	1.0000	0.0301	0.0035	0.0075	0.2921	0.0000	0.3667	0.1033	0.0167	0.1733	0.0067
180.0000	1.0000	0.0301	0.0035	0.0000	0.2997	0.0000	0.3667	0.1033	0.0167	0.1733	0.0067

Table 3-5
Case 4 Results

	Mode of Failure				
Expert	DWL	DWHL	DWR	DWHR	CDWR
A	0.05	0.00	0.00	0.00	0.00
B	0.25	0.04	0.32	0.02	0.06
C	0.00	0.00	0.00	0.00	0.00
Average	0.10	0.013	0.107	0.007	0.02

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3-2. L. Greimann et al., "Reliability Analysis of Steel Containment Strength," NUREG/CR-2442, Ames Laboratory, June 1982.

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Individual Elicitations for Issue 3

Expert A's Elicitation

Peach Bottom Containment Failure

Description of Expert A's Rationale/Methodology

The Expert gave his assessment in the form of cumulative distribution f ctions for each failure mode over the pressure range. For cases 1 and 2, Expert A provided the following information.

Pressure	WWLaW	DWL	DWHL	WWRaW	WWRbW	DWR
120	0	0	0	0	0	0
125	-	0	-	0	0	0
130	.05	0	-	0	0	0
135	-	0	-	0	0	0
140	.2	0	.1	0	0	0
145	.5	0	-	0	0	0
150	.9	0	.2	0	0	0
155	.99	0	-	.15	0	0
160	1	0	-	.5	0	0
165	1	-	-	.8	0	0
170	1	.2	.5	-	0	0
175	1	-	-	-	.05	0
180	1	.5	-	1	.2	0
185	1	.8	-	1	.5	0
190	1	.95	.8	1	.8	0
195	1	-	-	1	.95	0
200	1	1	-	1	1	0
202.5	1	1	-	1	1	.05
205	1	1	-	1	1	.25
210	1	1	.95	1	1	.5
215	1	1	-	1	1	-
220	1	1	-	1	1	.55
225	1	1	-	1	1	-
230	1	1	-	1	1	.9
235	1	1	-	1	1	-
240	1	1	1	1	1	1

Comments on Cases 1 & 2

1. Wetwell leak no bypass (WWLaW)-Discontinuity strains at T-stiffeners reach 4% at 150 psig. From a criterion developed for MARK I failure limits, this 4% strain is equivalent to a uniaxial ductility limit of 19%. Because the general strain state in the far field regions of the shell at the 50% probability (pressure = 145 psig) is at or below yield, this mode is predominantly a leakage mode. The 50% probability corresponding to 145 psig is based on the fact that a peak strain of 3.5% is reached at that pressure. This is of the same order of magnitude as strains measured in EPRI containment experiments where small, 1 to 2-in.,

leaks occurred. At the 20% probability (140 psig), the far field strain is still elastic. Therefore, if a crack initiates at a pressure of 140 psig, it will be arrested in the elastic region of the shell or by the adjacent stiffener which is about 3 ft away. An opening larger than 1.8 ft^2 is unlikely to develop.

2. Unlike location WWLaW, the membrane strain is less dominant for WWLbW. However, it is still a local strain concentration. The material fails at higher surface strain; hence, higher failure pressures. This mode is likely to develop into a rupture mode very quickly and is, therefore, not considered (see WWRbW). The crack would unzip in the hoop direction where no crack arrest mechanism exists.

3. For the DWL (at the downcomers), the highest surface strain is in the drywell, but failure there would lag the wet well. Failure at this location develops due to a bending strain. Because of the constraining effect of the floor, the failure size could not grow to a rupture.

4. For DWHL, a large uncertainty exists due to uncertainties in bolt pre-load, bolt relaxation, and degradation of the gasket material. Up to 40 mil resiliency is estimated to remain in the gasket material depending on age. Since gaskets are replaced periodically and are not allowed to deteriorate, there is no reason to assume that more than a 50% reduction in resiliency can occur.

5. For WWRaW or WWRbW, rupture mode develops only if the WWLaW crack arrests too soon before leakage is large enough. The probability distribution curve is steeper in the early range of pressure for WWRaW due to the fact that failure could evolve very rapidly from a point where the peak strain grows nonuniformly with pressure. For WWRbW, the distribution function is symmetric about the midpoint due to the fact that failure cannot be pinpointed to a point or a small region, but could occur anywhere over a large area where the peak strain would grow uniformly with pressure. This is a flatter curve because: (a) the discontinuity at this location is not as strong as at WWRaW, and (b) the strain at this location is predominantly bending unlike the WWRaW case where the strain is membrane. Failure by bending requires much higher surface strains, hence higher failure pressure.

6. For DWR (in the main body of the drywell near penetration), rupture pressure of the shield wall is 240 psig with yielding of reinforcement beginning at 200 psig. Drywell rupture occurs as a result of the loss of the concrete wall back support. This loss of support occurs in stages. First, the rebar in the shielding wall begins to yield and deform with little additional load up to about 1.5% strain. This stage is followed by significant strain hardening in the rebars and rebar deformation slows down significantly until ultimate tensile strength is realized. When this occurs, the rebar becomes unstable and deforms rapidly with a catastrophic decrease in load carrying capacity. These stages are reflected in the shape of the probability distribution curve. The first S in

this curve (200 to 210 psig) corresponds to the first stage or the flat portion of the rebar stress-strain curve and the second S corresponds to the strain hardening portion of the rebar stress-strain curve.

The cumulative failure probability by pressure i is formed by taking the difference between 1.0 and the product of the success probabilities of each mode and subtract from one:

p(j,i) = 1 - (1-p(j,i,m))*..*(1-p(j,i,m)).

For example, at 155 psig, WWLaW = .95, DWL = 0, DWHL = .2750, WWRaW =.15, and WWRbW = DWR = 0. So PT(150) = 1 - (1-.95) * (1-0) * (1-.275) * (1-.15) *(1-0) * (1-0) = 1 .05 * .7258 * .85 = .9692.

In order to calculate the conditional probability of failure at a specific pressure, the following formula is used:

c(j,i,m) = [(2-p(j,i)-p(j,i-1)) * (p(j,i,m)-p(j,i-1,m))]/
[(2-p(j,i,m)-p(j,i-1,m)) * (p(j,i)-p(j,i-1))].

When the probability of a particular mode goes to 1.0, its conditional probability is set to zero for all higher pressures since there was no chance of that failure mode occurring in that pressure interval and then a new total cumulative is calculated with the remaining failure modes. For example: at 155 psig, c(WWLaW,150) = (2-.9692-.9200) * (.95-.90) / (2-.95-.90) * (.9692-.92) = .7510.

Linear interpolation between points and extrapolation at the high pressure end (by continuing with the conditionals calculated at the point where the last mode went to 1.0) is used to create Table A-1, which is then converted to Tables A-2 and A-3.

Case 3 was divided into two subcases. For case 3a, the drywell structural temperature is 800°F and for case 3b, the temperature is 1200°F. For case 3a, Expert A gave the following information:

Pressure	WWLaW	DWL	DWHL
60	0	0	0
65	0	0	-
70	0	0	-
75	0	0	-
80	0	0	.1
85	0	0	-
90	0	0	.2
95	0	0	-
100	0	0	
105	0	0	-

Pressure	WWLaW	DWL	DWHL
110	0	0	.5
115	0	0	-
120	0	0	-
125	-	-	-
130	.05	.2	.8
135	-	-	-
140	.2	.5	-
145	.5	.8	-
150	.9	.95	.95
155	.99	-	-
160	1	1	-
165	1	1	-
170	1	1	-
175	1	1	-
180	1	1	1

Comments for Case 3a:

1. WWLbW, WWRaW, and WWRbW can not occur since temperature is at saturation in wetwell. Failure will occur first in the drywell due to the high temperatures or same as case 1 or 2 for WWLaW.

2. For DWL (at the downcomers), the difference with case 1 is a reduction of material strength (both yield and ultimate) due to 800°F. A 25% reduction was assumed and the failure pressures were adjusted accordingly.

3. For DWHL, the gasket was assumed to lose all its resiliency at 800°F.

The data manipulation is similar to that in cases 1 & 2. The results are shown in Tables A-4, A-5, and A-6.

For cases 3b and 4, Expert A gave the following tabular information for the probability of drywell leak for four pressures for a range of temperatures:

	Pressure (psig)			
Temperature	5	10	15	90
800	0	0	0	0
850	0	-	-	.1
900	0	0	.05	.6
950	0	-	-	-
1000	0	.05	.15	.8
1050	0	-	-	-
1100	0	.2	.5	-
1150	0	.35	.95	-
1200	.05	.5	1	1

For the 90 psig case, the failures are dominated by the behavior of the material under high temperatures. Above 800°F the material begins to exhibit thermal creep in addition to enhanced plastic flow. The combination of high pressure (90 psig) and thermal softening causes the probability distribution curve to be steep in the initial stages of temperature where accelerated thermal effects occur. For the low pressure regime (<15 psig), the effects of high temperature described above become more dominant in the high temperature range when the pressure is low. This is reflected in a steep rise in the distribution curve in the 1000°F to 1200°F range. In both of these cases, the material properties are assumed to degrade by 90%.

For Case [illegible], the 1200°F curve was used. For case 4, since the pressure is nominal after other failures, DWL = .05 (i.e., 5 psig at 1200°F) was used.

Tables A-7, A-8, and A-9 contain the results of manipulating Expert A's conclusions for case 3B.

Table A-1
Results for Expert A: Cases 1 and 2

Pressure (psig)	Cumulative Probability	Conditional Probability of Failure in Mode I at Pressure J									
		[illegible] W	WWLbW	WWRaW	WWRbW	CWWR	DWL	DWHL	DWR	DWHR	CDWR
90.0000	0.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000
95.0000	0.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000
100.0000	0.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000
105.0000	0.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000
110.0000	0.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000
115.0000	0.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000
120.0000	0.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000
125.0000	0.0434	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000
130.0000	0.0975	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000
135.0000	0.1906	0.7550	0.0000	0.0000	0.0000	0.0000	0.0000	0.2450	0.0000	0.0000	0.0000
140.0000	0.2800	0.7657	0.0000	0.0000	0.0000	0.0000	0.0000	0.2343	0.0000	0.0000	0.0000
145.0000	0.5750	0.8898	0.0000	0.0000	0.0000	0.0000	0.0000	0.1102	0.0000	0.0000	0.0000
150.0000	0.9200	0.9565	0.0000	0.0000	0.0000	0.0000	0.0000	0.0435	0.0000	0.0000	0.0000
155.0000	0.9692	0.8627	0.0000	0.0655	0.0000	0.0000	0.0000	0.0519	0.0000	0.0000	0.0000
160.0000	1.0000	0.6862	0.0000	0.2593	0.0000	0.0000	0.0000	0.0545	0.0000	0.0000	0.0000
165.0000	1.0000	0.0000	0.0000	0.7901	0.0000	0.0000	0.0970	0.1129	0.0000	0.0000	0.0000
170.0000	1.0000	0.0000	0.0000	0.6088	0.0000	0.0000	0.1790	0.2122	0.0000	0.0000	0.0000
175.0000	1.0000	0.0000	0.0000	0.6131	0.0472	0.0000	0.1905	0.1493	0.0000	0.0000	0.0000
180.0000	1.0000	0.0000	0.0000	0.6871	0.0857	0.0000	0.1304	0.0968	0.0000	0.0000	0.0000
185.0000	1.0000	0.0000	0.0000	0.0000	0.2961	0.0000	0.5499	0.1540	0.0000	0.0000	0.0000
190.0000	1.0000	0.0000	0.0000	0.0000	0.3612	0.0000	0.5057	0.1331	0.0000	0.0000	0.0000
195.0000	1.0000	0.0000	0.0000	0.0000	0.4379	0.0000	0.4866	0.0755	0.0000	0.0000	0.0000
200.0000	1.0000	0.0000	0.0000	0.0000	0.4348	0.0000	0.4348	0.1304	0.0000	0.0000	0.0000
205.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5526	0.4474	0.0000	0.0000
210.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5769	0.4231	0.0000	0.0000
215.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.7800	0.2200	0.0000	0.0000
220.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.8043	0.1957	0.0000	0.0000
225.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3718	0.6282	0.0000	0.0000
230.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3000	0.7000	0.0000	0.0000
235.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.5000	0.0000	0.0000
240.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.5000	0.0000	0.0000
245.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.5000	0.0000	0.0000
250.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.5000	0.0000	0.0000
255.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.5000	0.0000	0.0000
260.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.5000	0.0000	0.0000
265.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.5000	0.0000	0.0000
270.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.5000	0.0000	0.0000
275.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5000	0.5000	0.0000	0.0000

Table A-2

Expert A: Cases 1 and 2 Data Conversion

Pressure (psig)	Independent Cumulative Failure Probabilities for Modes: WWLaW	DWL	DWEL	WWRaW	WWRbW	DWR	Cumulative Probability: All Modes	Cumulative Failure Probabilities for Remaining Modes: (1)	(2)	(3)
90.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
95.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
100.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
105.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
110.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
115.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
120.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
125.0000	0.0250	0.0000	0.0250	0.0000	0.0000	0.0000	0.0494	0.0250	0.0250	0.0250
130.0000	0.0500	0.0000	0.0500	0.0000	0.0000	0.0000	0.0975	0.0500	0.0500	0.0500
135.0000	0.1250	0.0000	0.0750	0.0000	0.0000	0.0000	0.1906	0.0750	0.0750	0.0750
140.0000	0.2000	0.0000	0.1000	0.0000	0.0000	0.0000	0.2800	0.1000	0.1000	0.1000
145.0000	0.5000	0.0000	0.1500	0.0000	0.0000	0.0000	0.5750	0.1500	0.1500	0.1500
150.0000	0.9000	0.0000	0.2000	0.0000	0.0000	0.0000	0.9200	0.2000	0.2000	0.2000
155.0000	0.9900	0.0000	0.2750	0.1500	0.0000	0.0000	0.9938	0.3838	0.2750	0.2750
160.0000	1.0000	0.0000	0.3500	0.5000	0.0000	0.0000	1.0000	0.6750	0.3500	0.3500
165.0000	1.0000	0.1000	0.4250	0.8000	0.0000	0.0000	1.0000	0.8965	0.4825	0.4250
170.0000	1.0000	0.2000	0.5000	0.8667	0.0000	0.0000	1.0000	0.9467	0.6000	0.5000
175.0000	1.0000	0.3500	0.5750	0.9333	0.0500	0.0000	1.0000	0.9825	0.7376	0.5750
180.0000	1.0000	0.5000	0.6500	1.0000	0.2000	0.0000	1.0000	1.0000	0.8600	0.6500
185.0000	1.0000	0.8000	0.7250	1.0000	0.5000	0.0000	1.0000	1.0000	0.9725	0.7250
190.0000	1.0000	0.9500	0.8000	1.0000	0.8000	0.0000	1.0000	1.0000	0.9980	0.8000
195.0000	1.0000	0.9900	0.8375	1.0000	0.9500	0.0000	1.0000	1.0000	0.9999	0.8375
200.0000	1.0000	1.0000	0.8750	1.0000	1.0000	0.0000	1.0000	1.0000	1.0000	0.8750
205.0000	1.0000	1.0000	0.9125	1.0000	1.0000	0.2500	1.0000	1.0000	1.0000	0.9344
210.0000	1.0000	1.0000	0.9500	1.0000	1.0000	0.5000	1.0000	1.0000	1.0000	0.9750
215.0000	1.0000	1.0000	0.9583	1.0000	1.0000	0.5250	1.0000	1.0000	1.0000	0.9802
220.0000	1.0000	1.0000	0.9667	1.0000	1.0000	0.5500	1.0000	1.0000	1.0000	0.9850
225.0000	1.0000	1.0000	0.9750	1.0000	1.0000	0.7250	1.0000	1.0000	1.0000	0.9933
230.0000	1.0000	1.0000	0.9833	1.0000	1.0000	0.9000	1.0000	1.0000	1.0000	0.9983
235.0000	1.0000	1.0000	0.9917	1.0000	1.0000	0.9500	1.0000	1.0000	1.0000	0.9996
240.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0333	1.0000	1.0000	1.0000	1.0000
245.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
250.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
255.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
260.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
265.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
270.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
275.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

(1) Without mode WWLaW.
(2) Without modes WWLaW and WWRaW.
(3) Without modes WWLaW, WWRaW, DWL, and WWRbW.

Table A-3
Expert A's Conditional Probabilities: Cases 1 and 2

Pressure (psig)	Conditional Failure Probability						Normalized Conditional Failure Probabilities					
	WWLaW	DWL	DWHL	WWRaW	WWRbW	DWR	WWLaW	DWL	DWHL	WWRaW	WWRbW	DWR
90.0000	0.5001	0.0000	0.5001	0.0000	0.0000	0.0000	0.5000	0.0000	0.5000	0.0000	0.0000	0.0000
95.0000	0.5001	0.0000	0.5001	0.0000	0.0000	0.0000	0.5000	0.0000	0.5000	0.0000	0.0000	0.0000
100.0000	0.5001	0.0000	0.5001	0.0000	0.0000	0.0000	0.5000	0.0000	0.5000	0.0000	0.0000	0.0000
105.0000	0.5001	0.0000	0.5001	0.0000	0.0000	0.0000	0.5000	0.0000	0.5000	0.0000	0.0000	0.0000
110.0000	0.5001	0.0000	0.5001	0.0000	0.0000	0.0000	0.5000	0.0000	0.5000	0.0000	0.0000	0.0000
115.0000	0.5001	0.0000	0.5001	0.0000	0.0000	0.0000	0.5000	0.0000	0.5000	0.0000	0.0000	0.0000
120.0000	0.5001	0.0000	0.5001	0.0000	0.0000	0.0000	0.5000	0.0000	0.5000	0.0000	0.0000	0.0000
125.0000	0.5001	0.0000	0.5001	0.0000	0.0000	0.0000	0.5000	0.0000	0.5000	0.0000	0.0000	0.0000
130.0000	0.5001	0.0000	0.5001	0.0000	0.0000	0.0000	0.5000	0.0000	0.5000	0.0000	0.0000	0.0000
135.0000	0.7554	0.0000	0.2451	0.0000	0.0000	0.0000	0.7550	0.0000	0.2450	0.0000	0.0000	0.0000
140.0000	0.7662	0.0000	0.2344	0.0000	0.0000	0.0000	0.7657	0.0000	0.2343	0.0000	0.0000	0.0000
145.0000	0.8957	0.0000	0.1109	0.0000	0.0000	0.0000	0.8896	0.0000	0.1102	0.0000	0.0000	0.0000
150.0000	0.9758	0.0000	0.0444	0.0000	0.0000	0.0000	0.9565	0.0000	0.0435	0.0000	0.0000	0.0000
155.0000	0.9548	0.0000	0.0574	0.0946	0.0000	0.0000	0.8627	0.0000	0.0519	0.0855	0.0000	0.0000
160.0000	0.6862	0.0000	0.0545	0.2593	0.0000	0.0000	0.6862	0.0000	0.0545	0.2593	0.0000	0.0000
165.0000	0.0000	0.1018	0.1184	0.8281	0.0000	0.0000	0.0000	0.0970	0.1129	0.7901	0.0000	0.0000
170.0000	0.0000	0.1838	0.2180	0.6254	0.0000	0.0000	0.0000	0.1790	0.2122	0.6088	0.0000	0.0000
175.0000	0.0000	0.2046	0.1603	0.6585	0.0507	0.0000	0.0000	0.1905	0.1493	0.6131	0.0472	0.0000
180.0000	0.0000	0.1304	0.0968	0.6871	0.0857	0.0000	0.0000	0.1304	0.0968	0.6871	0.0857	0.0000
185.0000	0.0000	0.6381	0.1787	0.0000	0.3436	0.0000	0.0000	0.5499	0.1540	0.0000	0.2961	0.0000
190.0000	0.0000	0.6941	0.1827	0.0000	0.4958	0.0000	0.0000	0.5057	0.1331	0.0000	0.3612	0.0000
195.0000	0.0000	0.7231	0.1122	0.0000	0.6508	0.0000	0.0000	0.4866	0.0755	0.0000	0.4379	0.0000
200.0000	0.0000	0.4348	0.1304	0.0000	0.4348	0.0000	0.0000	0.4348	0.1304	0.0000	0.4348	0.0000
205.0000	0.0000	0.0000	0.5666	0.0000	0.0000	0.4586	0.0000	0.0000	0.5526	0.0000	0.0000	0.4474
210.0000	0.0000	0.0000	0.6084	0.0000	0.0000	0.4462	0.0000	0.0000	0.5769	0.0000	0.0000	0.4231
215.0000	0.0000	0.0000	0.7818	0.0000	0.0000	0.2205	0.0000	0.0000	0.7800	0.0000	0.0000	0.2200
220.0000	0.0000	0.0000	0.8068	0.0000	0.0000	0.1962	0.0000	0.0000	0.8043	0.0000	0.0000	0.1957
225.0000	0.0000	0.0000	0.3846	0.0000	0.0000	0.6499	0.0000	0.0000	0.3718	0.0000	0.0000	0.6282
230.0000	0.0000	0.0000	0.3280	0.0000	0.0000	0.7653	0.0000	0.0000	0.3000	0.0000	0.0000	0.7000
235.0000	0.0000	0.0000	0.5556	0.0000	0.0000	0.5556	0.0000	0.0000	0.5000	0.0000	0.0000	0.5000
240.0000	0.0000	0.0000	0.5556	0.0000	0.0000	0.5556	0.0000	0.0000	0.5000	0.0000	0.0000	0.5000
245.0000	0.0000	0.0000	0.5556	0.0000	0.0000	0.5556	0.0000	0.0000	0.5000	0.0000	0.0000	0.5000
250.0000	0.0000	0.0000	0.5556	0.0000	0.0000	0.5556	0.0000	0.0000	0.5000	0.0000	0.0000	0.5000
255.0000	0.0000	0.0000	0.5556	0.0000	0.0000	0.5556	0.0000	0.0000	0.5000	0.0000	0.0000	0.5000
260.0000	0.0000	0.0000	0.5556	0.0000	0.0000	0.5556	0.0000	0.0000	0.5000	0.0000	0.0000	0.5000
265.0000	0.0000	0.0000	0.5556	0.0000	0.0000	0.5556	0.0000	0.0000	0.5000	0.0000	0.0000	0.5000
270.0000	0.0000	0.0000	0.5556	0.0000	0.0000	0.5556	0.0000	0.0000	0.5000	0.0000	0.0000	0.5000
275.0000	0.0000	0.0000	0.5556	0.0000	0.0000	0.5556	0.0000	0.0000	0.5000	0.0000	0.0000	0.5000

Due to small errors, the conditional probabilities calculated did not sum precisely to 1.0; therefore, normalized by sum.

Table A-4
Results for Expert A: Case 3A

Pressure (psig)	Cumulative Probability	Conditional Probability of Failure in Mode I at Pressure J									
		WWLaW	WWLbW	WWRaW	WWRbW	CWWR	DWL	DWHL	DWR	DWHR	CDWR
50.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
55.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
60.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
65.0000	0.0250	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
70.0000	0.0500	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
75.0000	0.0750	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
80.0000	0.1000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
85.0000	0.1500	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
90.0000	0.2000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
95.0000	0.2750	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
100.0000	0.3500	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
105.0000	0.4250	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
110.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
115.0000	0.5750	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
120.0000	0.6500	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
125.0000	0.7587	0.0583	0.0000	0.0000	0.0000	0.0000	0.2841	0.6475	0.0000	0.0000	0.0000
130.0000	0.8480	0.0565	0.0000	0.0000	0.0000	0.0000	0.2561	0.6874	0.0000	0.0000	0.0000
135.0000	0.9076	0.1657	0.0000	0.0000	0.0000	0.0000	0.4171	0.4171	0.0000	0.0000	0.0000
140.0000	0.9500	0.1465	0.0000	0.0000	0.0000	0.0000	0.4268	0.4268	0.0000	0.0000	0.0000
145.0000	0.9913	0.2761	0.0000	0.0000	0.0000	0.0000	0.5128	0.2111	0.0000	0.0000	0.0000
150.0000	0.9998	0.4331	0.0000	0.0000	0.0000	0.0000	0.3898	0.1772	0.0000	0.0000	0.0000
155.0000	1.0000	0.4400	0.0000	0.0000	0.0000	0.0000	0.4400	0.1200	0.0000	0.0000	0.0000
160.0000	1.0000	0.4444	0.0000	0.0000	0.0000	0.0000	0.4444	0.1111	0.0000	0.0000	0.0000
165.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
170.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
175.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
180.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
185.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
190.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
195.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
200.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
205.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
210.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
215.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
220.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
225.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000

Table A-5
Expert A: Case 3A Data Conversion

Pressure (psig)	Independent Cumulative Failure Probabilities for Modes						Cumulative Failure Probabilities All Modes
	WWLaW	DWL	DWHL	WWRaW	WWRbW	DWR	
60.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
65.0000	0.0000	0.0000	0.0250	0.0000	0.0000	0.0000	0.0250
70.0000	0.0000	0.0000	0.0500	0.0000	0.0000	0.0000	0.0500
75.0000	0.0000	0.0000	0.0750	0.0000	0.0000	0.0000	0.0750
80.0000	0.0000	0.0000	0.1000	0.0000	0.0000	0.0000	0.1000
85.0000	0.0000	0.0000	0.1500	0.0000	0.0000	0.0000	0.1500
90.0000	0.0000	0.0000	0.2000	0.0000	0.0000	0.0000	0.2000
95.0000	0.0000	0.0000	0.2750	0.0000	0.0000	0.0000	0.2750
100.0000	0.0000	0.0000	0.3500	0.0000	0.0000	0.0000	0.3500
105.0000	0.0000	0.0000	0.4250	0.0000	0.0000	0.0000	0.4250
110.0000	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000	0.5000
115.0000	0.0000	0.0000	0.5750	0.0000	0.0000	0.0000	0.5750
120.0000	0.0000	0.0000	0.6500	0.0000	0.0000	0.0000	0.6500
125.0000	0.0250	0.1000	0.7250	0.0000	0.0000	0.0000	0.7587
130.0000	0.0500	0.2000	0.8000	0.0000	0.0000	0.0000	0.8480
135.0000	0.1250	0.3500	0.8375	0.0000	0.0000	0.0000	0.9076
140.0000	0.2000	0.5000	0.8750	0.0000	0.0000	0.0000	0.9500
145.0000	0.5000	0.8000	0.9125	0.0000	0.0000	0.0000	0.9913
150.0000	0.9000	0.9500	0.9500	0.0000	0.0000	0.0000	0.9998
155.0000	0.9500	0.9750	0.9583	0.0000	0.0000	0.0000	0.9999
160.0000	1.0000	1.0000	0.9667	0.0000	0.0000	0.0000	1.0000
165.0000	1.0000	1.0000	0.9750	0.0000	0.0000	0.0000	1.0000
170.0000	1.0000	1.0000	0.9833	0.0000	0.0000	0.0000	1.0000
175.0000	1.0000	1.0000	0.9917	0.0000	0.0000	0.0000	1.0000
180.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	1.0000

Table A-6
Expert A's Conditional Probabilities: Cases 3A

Pressure (psig)	Conditional Failure Probability WWLaW	DWL	DWHL	WWRaW	WWRbW	DWR	Normalized Conditional Failure Probabilities WWLaW	DWL	DWHL	WWRaW	WWRbW	DWR
60.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
65.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
70.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
75.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
80.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
85.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
90.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
95.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
100.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
105.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
110.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
115.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
120.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
125.0000	0.0689	0.2863	0.6529	0.0000	0.0000	0.0000	0.0683	0.2841	0.6476	0.0000	0.0000	0.0000
130.0000	0.0572	0.2580	0.6953	0.0000	0.0000	0.0000	0.0565	0.2561	0.6874	0.0000	0.0000	0.0000
135.0000	0.1686	0.4244	0.4244	0.0000	0.0000	0.0000	0.1657	0.4171	0.4171	0.0000	0.0000	0.0000
140.0000	0.1503	0.4379	0.4379	0.0000	0.0000	0.0000	0.1465	0.4268	0.4268	0.0000	0.0000	0.0000
145.0000	0.3287	0.6104	0.2513	0.0000	0.0000	0.0000	0.2761	0.5128	0.2111	0.0000	0.0000	0.0000
150.0000	0.7059	0.5353	0.2888	0.0000	0.0000	0.0000	0.4331	0.3898	0.1772	0.0000	0.0000	0.0000
155.0000	0.5088	0.5088	0.1388	0.0000	0.0000	0.0000	0.4400	0.4400	0.1200	0.0000	0.0000	0.0000
160.0000	0.4444	0.4444	0.1111	0.0000	0.0000	0.0000	0.4444	0.4444	0.1111	0.0000	0.0000	0.0000
165.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
170.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
175.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
180.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000

Due to small errors, the conditional probabilities calculated did not sum precisely to 1.0; therefore, normalized by sum.

Table A-7
Results for Expert A: Case 3B

Pressure (psig)	Cumulative Probability	Conditional Probability of Failure in Mode I at Pressure J									
		WWLaW	WWLbW	WWRaW	WWRbW	CWWR	DWL	DWHL	DWR	DWHR	CDWR
5.0000	0.0500	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
10.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
15.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
20.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
25.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
30.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
35.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
40.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
45.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
50.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
55.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
60.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
65.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
70.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
75.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
80.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
85.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
90.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
95.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
100.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
105.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
110.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
115.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
120.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
125.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
130.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
135.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
140.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
145.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
150.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
155.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
160.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
165.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
170.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
175.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
180.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000

Table A-8
Expert A: Case 3B Data Conversion

Pressure (psig)	Independent Cumulative Failure Probabilities for Modes						Cumulative Failure Probabilities: All Modes
	WWLaW	DWL	DWHL	WWRaW	WWRbW	DWR	
5.0000	0.0000	0.0500	0.0000	0.0000	0.0000	0.0000	0.0500
10.0000	0.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.5000
15.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
20.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
25.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
30.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
35.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
40.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
45.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
50.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
55.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
60.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
65.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
70.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
75.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
80.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
85.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
90.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
95.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
100.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
105.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
110.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
115.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
120.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
125.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
130.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
135.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
140.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
145.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
150.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
155.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
160.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
165.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
170.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
175.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000
180.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000

Table A-9
Expert A's Conditional Probabilities: Case 3B

Pressure (psig)	Independent Cumulative Failure Probabilities for Modes					
	WWLaW	DWL	DWHL	WWRaW	WWRbW	DWR
5.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
10.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
15.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
20.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
25.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
30.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
35.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
40.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
45.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
50.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
55.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
60.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
65.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
70.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
75.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
80.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
85.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
90.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
95.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
100.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
105.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
110.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
115.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
120.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
125.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
130.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
135.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
140.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
145.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
150.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
155.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
160.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
165.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
170.0	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
175.0	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
180.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000

Expert B's Elicitation

Peach Bottom Containment Failure

Description of Expert B's Rationale/Methodology

The Expert defined ten failure mode/locations and gave probability curves versus pressure for each mode for each case. The values in each column are joint probabilities of failure in each mode given no failure at lower pressures.

For cases 1 and 2, Expert B gave the following tabular information:

	Pressure (psig)						
Modes	90	110	135	160	170	180	195
WWLaW	0.0	0.02	0.04	0.06	0.07	0.07	0.07
WWLbW	0.0	0.0	0.02	0.03	0.05	0.05	0.05
WWRaW	0.0	0.02	0.02	0.07	0.09	0.12	0.12
WWRbW	0.0	0.0	0.02	0.05	0.04	0.07	0.07
CWWR	0.0	0.0	0.02	0.12	0.16	0.35	0.38
DWL	0.0	0.01	0.01	0.03	0.06	0.06	0.06
DWHL	0.0	0.01	0.02	0.05	0.08	0.12	0.14
DWR	0.0	0.0	0.01	0.01	0.01	0.04	0.04
DWHR	0.0	0.0	0.01	0.01	0.01	0.05	0.05
CDWR	0.0	0.0	0.0	0.0	0.01	0.02	0.02
Total	0.0	0.06	0.17	0.43	0.58	0.95	1.00

Comments for cases 1 and 2:

No chance of failure until 90 psig based on engineering judgment. In the pressure range from 150 to 180 psig, the probabilities are based on calculations and reports which are based on all types of pressure vessels. As the pressure increases there is more energy to tear the steel and, thus, there is a greater chance for rupture. With less stored energy, it is possible to arrest a crack and maintain a leak. For Case 2, the pressure rise is slow enough to be considered static and therefore is the same as Case 1. In order to calculate the cumulative failure probability, use the formula:

$$p(\text{fail by } p_i) = p(\text{fail by } p_{i-1}) + p(\text{fail between } p_{i-1} < p > p_i) * p(\text{not failing by } p_{i-1}).$$

The cumulative is then: PT(90)=0, PT(110)=.06, PT(135)=.2198, PT(160)=.5553, PT(170)=.8132, PT(180)=.9907, PT(195)=1.0000.

The conditional probability of failure at pressure i in mode j is the probability at pressure i for mode j divided by the total conditional at pressure i.

Linear interpolation between points and, in order to extend the curves on the upper side, it was assumed that the conditional probabilities remain fixed above 165 psig. The results for cases 1 and 2 are shown in Table B-1.

Case 3

Expert B indicated that this case is more complicated due to the effects of temperature. To treat this case properly, the expert stated that he would need pressure and temperature histories. The expert divided the temperature range into two regions centered on 800 and 1200°F. For both cases, the wetwell temperature is limited to the suppression pool saturation temperature (300 to 350°F). The expert indicated that when the drywell temperature exceeded the wetwell temperature, there was a greater likelihood that failure would occur in the drywell.

For case 3a, Expert B gave the following probabilities:

	Pressure (psig)					
Modes	75	95	115	135	150	165
WWLaW	0.0	0.0	0.02	0.05	0.06	0.06
WWLbW	0.0	0.0	0.01	0.02	0.03	0.03
WWRaW	0.0	0.0	0.02	0.03	0.06	0.06
WWRbW	0.0	0.0	0.0	0.03	0.04	0.04
CWWR	0.0	0.0	0.0	0.09	0.13	0.14
DWL	0.0	0.01	0.02	0.04	0.05	0.05
DWHL	0.0	0.02	0.05	0.09	0.16	0.18
DWR	0.0	0.0	0.0	0.01	0.05	0.05
DWHR	0.0	0.0	0.0	0.01	0.36	0.38
CDWR	0.0	0.0	0.0	0.0	0.01	0.01
Total	0.0	0.03	0.12	0.37	0.95	1.00

The cumulative is PT(75)=0, PT(95)=.03, PT(115)=.1464, PT(135)=.4622, PT(150)=.9731, PT(165)=1.0.

Case 3a assumes 800°F in drywell and 300°F in wetwell. The failure probability is based on a one hour exposure to 800°F. The yield strength at this temperature is approximately 85% of that at ambient temperatures. The general trend is an increase in the probability of failure with an increase in temperature. There could be some cases, however, where higher temperatures do not necessarily mean higher failure probability (e.g., the thermal growth of the drywell shell may help if the shell impinges on the concrete wall; this is a secondary effect). At this temperature, an increase in exposure time to 24 h would not change these probabilities.

Interpolation was used to form Table B-2.

For case 3b, Expert B provided the following conclusions:

	Pressure (psig)				
Modes	25	40	50	55	60
WWLaW	0.0	0.0	0.0	0.0	0.0
WWLbW	0.0	0.0	0.0	0.0	0.0
WWRaW	0.0	0.0	0.0	0.0	0.0
WWRbW	0.0	0.0	0.0	0.0	0.0
CWWR	0.0	0.0	0.0	0.0	0.0
DWL	0.0	0.01	0.08	0.10	0.10
DWHL	0.0	0.24	0.28	0.30	0.31
DWR	0.0	0.0	0.03	0.05	0.05
DWHR	0.0	0.0	0.23	0.50	0.52
CDWR	0.0	0.0	0.0	0.02	0.02
Total	0.0	0.25	0.62	0.97	1.00

The cumulative is PT(25)=0, PT(40)=.25, PT(50)=.7150, PT(55)=.9915, PT(60)=1.0.

Case 3b assumes 1200°F in the drywell and 350°F in the wetwell. Failure will occur in the drywell at lower pressures than those that could cause failure in the wetwell. The yield strength at this temperature is approximately 30% of that at ambient temperatures. The likely leakage would be at flange openings and degraded seals and gaskets. Failure probabilities are based on one hour of exposure. With 24 h of exposure, the leak modes (6 and 7) may change to rupture. Given leak modes in 1 h at 60 psig and additional exposure, these will definitely change to rupture. The change will occur at 50 psig. However, a leak will depressurize the containment in 2 h so no additional failure occurs. Case 3b results are shown in Table B-3.

MODE	50	60
DWR	.2	.2
DWHR	.5	.5
CDWR	.2	.3
Total	.9	1

For case 4, Expert B provided the following probabilities for different temperatures.

	1 Hour						24 Hours	
	Temperature (°F)						Temperature(°F)	
Mode	600	800	900	1000	1100	1200	1000	1200
DWL	0.0	0.1	0.18	0.2	0.22	0.25	0.24	0.3
DWHL	0.0	0.0	0.0	0.0	0.03	0.04	0.0	0.15
DWR	0.0	0.05	0.08	0.13	0.25	0.32	0.17	0.3
DWHR	0.0	0.0	0.0	0.0	0.01	0.02	0.0	0.15
CDWR	0.0	0.0	0.0	0.01	0.02	0.06	0.01	0.10
Total	0.0	0.15	0.26	0.34	0.53	0.69	0.42	1.0

Case 4 assumes that containment failure has already occurred so that pressure is low and assesses that probability of additional failure due to high drywell temperatures for exposure times of 1 and 24 h. The composite probabilities at 900 and 1000°F are based on high temperature analyses performed by the expert. At 1200°F, the failure mode will be catastrophic failure caused by thermal buckling. For this analysis, the values at 1200°F for case 4 are used.

Sources of Uncertainty

The expert indicated that the major sources of uncertainty in his assessment were uncertainties in the material properties and the uncertainty in fabrication details. For example, there could be residual stresses around welds or areas of local stress concentration which could affect the strength of the containment. For Case 3, the expert said that to treat the problem properly, he would need the time histories of pressure and temperature. Not knowing these introduces some additional uncertainty into the results.

Some of the uncertainty for Case 3 could be removed if typical pressure and temperature histories from thermal-hydraulic codes could be supplied for the scenarios of interest.

Table B-1
Results of Expert B: Cases 1 and 2

Pressure (psig)	Cumulative Probability	Conditional Probability of Failure in Mode I at Pressure J									
		WWLaW	WWLbW	WWRaW	WWRbW	CWWR	DWL	DWRL	DWR	DWIR	CDWR
90.0000	0.0000	0.3333	0.0000	0.3333	0.0000	0.0000	0.1667	0.1667	0.0000	0.0000	0.0000
95.0000	0.0150	0.3333	0.0000	0.3533	0.0000	0.0000	0.1567	0.1667	0.0000	0.0000	0.0000
100.0000	0.0300	0.3333	0.0000	0.3333	0.0000	0.0000	0.1667	0.1667	0.0000	0.0000	0.0000
105.0000	0.0450	0.3333	0.0000	0.3333	0.0000	0.0000	0.1667	0.1667	0.0000	0.0000	0.0000
110.0000	0.0600	0.3333	0.0000	0.3333	0.0000	0.0000	0.1667	0.1667	0.0000	0.0000	0.0000
115.0000	0.0920	0.3137	0.0235	0.2902	0.0235	0.0235	0.1451	0.1569	0.0118	0.0118	0.0000
120.0000	0.1239	0.2941	0.0470	0.2470	0.0471	0.0471	0.1235	0.1472	0.0235	0.0235	0.0000
125.0000	0.1559	0.2745	0.0706	0.2039	0.0706	0.0706	0.1020	0.1372	0.0353	0.0253	0.0000
130.0000	0.1878	0.2549	0.0941	0.1607	0.0942	0.0942	0.0804	0.1275	0.0470	0.0470	0.0000
135.0000	0.2198	0.2353	0.1176	0.1176	0.1177	0.1177	0.0588	0.1177	0.0588	0.0588	0.0000
140.0000	0.2869	0.2161	0.1080	0.1266	0.1174	0.1500	0.0610	0.1175	0.0517	0.0517	0.0000
145.0000	0.3540	0.1970	0.0985	0.1357	0.1171	0.1823	0.0632	0.1171	0.0446	0.0446	0.0000
150.0000	0.4211	0.1778	0.0889	0.1447	0.1169	0.2145	0.0654	0.1170	0.0374	0.0374	0.0000
155.0000	0.4882	0.1587	0.0794	0.1538	0.1166	0.2468	0.0676	0.1165	0.0303	0.0303	0.0000
160.0000	0.5553	0.1395	0.0698	0.1628	0.1163	0.2791	0.0698	0.1163	0.0232	0.0232	0.0000
165.0000	0.6842	0.1301	0.0780	0.1590	0.0927	0.2775	0.0866	0.1271	0.0202	0.0202	0.0086
170.0000	0.8132	0.1207	0.0862	0.1532	0.0690	0.2759	0.1034	0.1379	0.0172	0.0172	0.0173
175.0000	0.9019	0.0972	0.0694	0.1408	0.0714	0.3222	0.0833	0.1321	0.0297	0.0349	0.0192
180.0000	0.9907	0.0737	0.0525	0.1263	0.0737	0.3684	0.0632	0.1263	0.0421	0.0526	0.0211
185.0000	0.9938	0.0725	0.0517	0.1242	0.0725	0.3723	0.0621	0.1309	0.0414	0.0517	0.0207
190.0000	0.9969	0.0712	0.0509	0.1221	0.0712	0.3761	0.0611	0.1354	0.0407	0.0509	0.0204
195.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200
200.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200
205.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200
210.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200
215.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200
220.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200
225.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200
230.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200
235.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200
240.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200
245.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200
250.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200
255.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200
260.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200
265.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200
270.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200
275.0000	1.0000	0.0700	0.0500	0.1200	0.0700	0.3800	0.0600	0.1400	0.0400	0.0500	0.0200

Table B-2
Results of Expert B: Case 3A

Pressure (psig)	Cumulative Probability	Conditional Probability of Failure in Mode I at Pressure J									
		WWLaW	WWLbW	WWRaW	WWRbW	CWWR	DWL	DWRL	DWR	DWRR	CDWR
55.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3333	0.6667	0.0000	0.0000	0.0000
60.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3333	0.6667	0.0000	0.0000	0.0000
60.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3333	0.6667	0.0000	0.0000	0.0000
65.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3333	0.6667	0.0000	0.0000	0.0000
70.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3333	0.6667	0.0000	0.0000	0.0000
75.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3333	0.6667	0.0000	0.0000	0.0000
80.0000	0.0075	0.0000	0.0000	0.0000	0.0000	0.0000	0.3333	0.6667	0.0000	0.0000	0.0000
85.0000	0.0150	0.0000	0.0000	0.0000	0.6900	0.0000	0.3333	0.6667	0.0000	0.0000	0.0000
90.0000	0.0225	0.0000	0.0000	0.0000	0.0000	0.0000	0.3333	0.6667	0.0000	0.0000	0.0000
95.0000	0.0300	0.0000	0.0000	0.0000	0.0000	0.0000	0.3333	0.6667	0.0000	0.0000	0.0000
100.0000	0.0591	0.0417	0.0208	0.0417	0.0000	0.0000	0.2917	0.6042	0.0000	0.0000	0.0000
105.0000	0.0882	0.0833	0.0417	0.0833	0.0000	0.0000	0.2500	0.5417	0.0000	0.0000	0.0000
110.0000	0.1173	0.1250	0.0625	0.1250	0.0000	0.0000	0.2083	0.4792	0.0000	0.0000	0.0000
115.0000	0.1464	0.1667	0.0833	0.1667	0.0000	0.0000	0.1667	0.4167	0.0000	0.0000	0.0000
120.0000	0.2254	0.1588	0.0760	0.1453	0.0203	0.0508	0.1520	0.3733	0.0068	0.0068	0.0000
125.0000	0.3043	0.1509	0.0687	0.1239	0.0405	0.1216	0.1374	0.3300	0.0135	0.0135	0.0000
130.0000	0.3833	0.1430	0.0614	0.1025	0.0608	0.1824	0.1227	0.2866	0.0203	0.0203	0.0000
135.0000	0.4622	0.1351	0.0541	0.0811	0.0811	0.2432	0.1061	0.2432	0.0270	0.0270	0.0000
140.0000	0.6325	0.1111	0.0466	0.0751	0.0681	0.2078	0.0896	0.2183	0.0756	0.1443	0.0035
145.0000	0.8028	0.0872	0.0391	0.0691	0.0551	0.1723	0.0711	0.1934	0.0441	0.2616	0.0070
150.0000	0.9731	0.0632	0.0316	0.0632	0.0421	0.1368	0.0526	0.1684	0.0526	0.3789	0.0105
155.0000	0.9821	0.0621	0.0311	0.0621	0.0414	0.1379	0.0518	0.1723	0.0518	0.3793	0.0104
160.0000	0.9910	0.0611	0.0305	0.0611	0.0407	0.1389	0.0509	0.1761	0.0509	0.3796	0.0102
165.0000	1.0000	0.0600	0.0300	0.0600	0.0400	0.1400	0.0500	0.1800	0.0500	0.3800	0.0100
170.0000	1.0000	0.0600	0.0300	0.0600	0.0400	0.1400	0.0500	0.1800	0.0500	0.3800	0.0100
175.0000	1.0000	0.0600	0.0300	0.0600	0.0400	0.1400	0.0500	0.1800	0.0500	0.3800	0.0100
180.0000	1.0000	0.0600	0.0300	0.0600	0.0400	0.1400	0.0500	0.1800	0.0500	0.3800	0.0100
185.0000	1.0000	0.0600	0.0300	0.0600	0.0400	0.1400	0.0500	0.1800	0.0500	0.3800	0.0100
190.0000	1.0000	0.0600	0.0300	0.0600	0.0400	0.1400	0.0500	0.1800	0.0500	0.3800	0.0100
195.0000	1.0000	0.0600	0.0300	0.0600	0.0400	0.1400	0.0500	0.1800	0.0500	0.3800	0.0100
200.0000	1.0000	0.0600	0.0300	0.0600	0.0400	0.1400	0.0500	0.1800	0.0500	0.3800	0.0100
205.0000	1.0000	0.0600	0.0300	0.0600	0.0400	0.1400	0.0500	0.1800	0.0500	0.3800	0.0100
210.0000	1.0000	0.0600	0.0300	0.0600	0.0400	0.1400	0.0500	0.1800	0.0500	0.3800	0.0100
215.0000	1.0000	0.0600	0.0300	0.0600	0.0400	0.1400	0.0500	0.1800	0.0500	0.3800	0.0100
220.0000	1.0000	0.0600	0.0300	0.0600	0.0400	0.1400	0.0500	0.1800	0.0500	0.3800	0.0100
225.0000	1.0000	0.0600	0.0300	0.0600	0.0400	0.1400	0.0500	0.1800	0.0500	0.3800	0.0100

Table B-3
Results of Expert B: Case 3B

Pressure (psig)	Cumulative Probability	Conditional Probability of Failure in Mode I at Pressure J									
		WWLaW	WWLbW	WWRaW	WWRbW	CTWR	DWL	DWBL	DWR	DWBR	CDWR
5.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0400	0.9600	0.0000	0.0000	0.0000
10.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0400	0.9600	0.0000	0.0000	0.0000
15.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0400	0.9600	0.0000	0.0000	0.0000
20.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0400	0.9600	0.0000	[illegible]	0.0000
25.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0400	0.9600	[illegible]	[illegible]	0.0000
30.0000	0.0833	0.0000	0.0000	0.0000	0.0000	0.0000	0.0400	0.9600	[illegible]	0.0000	0.0000
35.0000	0.1667	0.0000	0.0000	0.0000	0.0000	0.0000	0.0400	0.9600	0.0000	0.0000	0.0000
40.0000	0.2500	0.0000	0.0000	0.0000	0.0000	0.0000	0.0400	0.9600	0.0000	0.0000	0.0000
45.0000	0.4825	0.0000	0.0000	0.0000	0.0000	0.0000	0.0845	0.7058	0.0242	0.1855	0.0000
50.0000	0.7150	0.0000	0.0000	0.0000	0.0000	0.0000	0.1290	0.4516	0.0484	0.3710	0.0000
55.0000	0.9915	0.0000	0.0000	0.0000	0.0000	0.0000	0.1021	0.3093	0.0515	0.5155	0.0206
60.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
65.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
70.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
75.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
80.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
85.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
90.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
95.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
100.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
105.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
110.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
115.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
120.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
125.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
130.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
135.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
140.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
145.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
150.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
155.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
160.0000	1.0000	0.0000	0.0000	0.0000	[illegible]	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
165.0000	1.0000	0.0000	0.0000	0.0000	[illegible]	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
170.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
175.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200
180.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1000	0.3100	0.0500	0.5200	0.0200

Expert C's Elicitation

Peach Bottom Containment Failure

Description of Expert C's Rationale/Methodology

Expert C limited his investigation to consideration of membrane stress; i.e., bending and thermal stresses were assumed to be self-limiting, which implied that they would not affect capacity. The membrane stresses were based on calculations documented in References C-1 and C-2 with extrapolations to higher pressures based on the equations for membrane stresses of various shells of revolution given in Reference C-3. Although it was recognized that failure initiates due to strain concentrations at design details, the equivalent free-field equivalent membrane strain was used to estimate the failure pressure. Based on the results of testing scale steel containment models,[C-4,C-5] the following approximate criteria were used.

No failure. The point at which membrane yielding of a steel plate section is first calculated to occur when beam and ring stiffeners are ignored.

Low probability of failure. General yield of section based on axisymmetric finite element calculations which include stiffeners and other local supports.

Median estimate. The point at which 1 to 2% equivalent strain arises in some section of the torus.

High probability of failure. The point at which 5% equivalent strain arises in some section of the torus.

Certain failure. The pressure at which membrane stress in the weakest plate section reaches the ultimate stress of the material.

The failure size depends on the growth of the initial crack. It was assumed that a crack is arrested only if it enters a region of plate material that is still elastic as determined from the membrane stresses.

In the wetwell, the maximum membrane stress occurs in the 0.604-in. plate just above the waterline, and consequently this is where failure is most likely to initiate. There is a small chance that a tear could initiate below the waterline. At higher pressure, a greater percentage of the wetwell plates are inelastic and an initial crack is more likely to grow; thus there is a higher probability of rupture.

In the drywell, contact with the shield building, which could impart additional strength to the shell, cannot be explicitly taken into account. To compensate for the effect of the shield building, the probability of drywell shell failure at low strains was decreased compared to the assumptions made for the wetwell. Since the membrane stress is uniform over a number of large areas in the drywell shell, the failure size is almost sure to correspond to rupture (catastrophic failure was felt to be precluded by interaction with the shield building).

The Expert assessed all four cases together by giving failure curves versus pressure for various temperatures.

Wetwell Failure

Pressure	Cum. Failure	Failure At Pres.	Conditional Probability At Pressure			
			WWLaW	WWLbW	WWRaW	WWRbW
125	0.0	0.0	0.0	0.0	0.0	0.0
140	0.01	0.01	0.9	0.1	0.0	0.0
150	0.2585	0.251	0.8088	0.0916	0.0199	0.0797
165	0.6307	0.502	0.2251	0.0259	0.0757	0.6733
170	0.9084	0.752	0.0904	0.0107	0.0452	0.8537
180	0.9955	0.951	0.0904	0.0105	0.0	0.8991
260	1.0	0.999	0.0	0.0	0.0	1.0

Assessed temperature in wetwell will be in 400°F range for all cases; therefore, only one curve.

Drywell Rupture (DWR)

CDF	200°F	400°F	600°F	800°F	1000°F	1200°F
0	155	150	125	105	90	58
.25	175	170	155	120	100	60
.5	190	190	190	170	110	63
.75	240	240	250	200	120	66
1	270	280	290	225	130	68

The 400°F, 800°F, and 1200°F curves were used for cases 1 and 2, 3a and 4a, and 3b and 4b, respectively.

For drywell head failure, the expert gave a FORTRAN program to calculate the failure pressure based on his uncertainty in the underlying parameters: DT = T(ave flange temp) - T(ave bolt temp), F_i = applied mechanical preload, S_p = seal performance parameter. All other parameters were considered reasonably well known.

DT(°F)	10	25	60	75	87	150	200
cdf(<600)	0	.025	.25	.50	.75	.975	1.0
DT(°F)	10	60	100	120	150	165	200
cdf(> = 600)	0	.125	.25	.50	.75	.875	1.0
F_i(kips)	75	95	100	107	125		
cdf	0	.25	.50	.75	1.0		

S_p(mils)	0	6	12	15	25	35	40
cdf	0	.01	.25	.5	.75	.999	1.0

S_p(mils)	0	6	8	10	15	40
cdf	0	.05	.5	.95	.999	1.0

The FORTRAN program was modified to allow an LHS sample of one hundred for DT, F_i, and S_p to be used to evaluate the probability of a certain size leak for different drywell temperatures at different pressures. The results were then analyzed to obtain the cumulative failure probability and the conditional probability of leak versus rupture at a temperature for the various pressures. The FORTRAN program is listed below:

```
      PROGRAM LEAKAREA
      DIMENSION EF(12), EB(12), EBT(12), EPSF(12), EPSB(12),
     ;          T(12), SIGY(12)
      DIMENSION ALHS(5,100)
      REAL KF, KBE  KBT, L[illegible]LA, LAMIN, LAMAX, LAINC, MULT1,
     ;     MULT2, MULT3, NU
C
C THIS PROGRAM CALCULATES THE LEAK AREA OF A PRESSURE UNSEATING
C HATCH AT A GIVEN TEMPERATURE AND PRESSURE FOR AN LHS SAMPLE OF
C THE BOLT PRELOAD, THE SEAL SPRINGBACK, AND THE DELTA T BETWEEN
C THE FLANGE AND THE BOLT
C
C DATA FOR PHYSICAL PARAMETERS
C
C T = THE FLANGE TEMPERATURE
C EF = THE ELASTIC MODULI FOR THE FLANGE MATERIAL
C EB = THE ELASTIC MODULI FOR THE BOLT MATERIAL IF THE PRESSURE
C      IS LESS THAN THE BOLT YIELD PRESSURE
C EBT = THE ELASTIC MODULI FOR THE BOLT IF THE PRESSURE IS
C       GREATER THAN THE BOLT YIELD PRESSURE
C EPSF = THERMAL STRAINS FOR FLANGE MATERIAL
C EPSB = THERMAL STRAINS FOR BOLT MATERIAL
C SIGY = YIELD STRENGTHS FOR BOLT MATERIAL (IN KSI)
C
      DATA T/ 70., 200., 300., 400., 500., 600., 700., 800.,
     ;        900., 1000., 1100., 1200./
      DATA EF/ 27.9E6, 27.8E6, 27.4E6, 27.0E6, 26.4E6, 25.7E6,
     ;          24.8E6, 23.4E6, 21.8E6, 20.6E6, 18.3E6, 17.0E6/
      DATA EB/ 2*31.5E6, 31.2E6, 30.9E6, 30.4E6, 29.9E6, 29.4E6,
     ;          28.8E6, 28.1E6, 27.0E6, 25.9E6, 24.5E6/
      DATA EBT/ 7*200.E3, 180.E3, 150.E3, 100.E3, 60.E3, 30.E3/
      DATA EPSF/ 0., .00076, .00141, .00214, .00295, .00383,
     ;           .00474, .00567, .00662, .00759, .00860, .00962/
      DATA EPSB/ 0., .00082, .00153, .00224, .00295, .00370,
     ;           .00453, .00540, .00630, .00720, .00820, .00920/
      DATA SIGY/ 105., 102.7, 99., 95.5, 90.1, 83.8, 76.6, 73.6,
     ;           65.5, 58., 50., 40./
      OPEN(UNIT=20,FILE='LHSLEAKAREA.OUT',STATUS='NEW',FORM=
     ; 'FORMATTED')
C
```

```
C DEFAULT DATA FOR PEACH BOTTOM DRYWELL HEAD FOLLOWS
C
C N = THE NUMBER OF BOLTS
C A = THE TENSILE AREA OF ONE BOLT
C L = THE GRIP LENGTH
C R = THE FLANGE RADIUS
C THICK = THE FLANGE THICKNESS
C NU = POISSON'S RATIO
C
      N = 68
      A = 4.292
      L = 36.
      R = 194.
      THICK = 1.25
      NU = 0.3
C
C  READ LHS FILE
C
      OPEN(UNIT = 55, STATUS = 'OLD', FILE = 'LHS.DAT')
      DO I = 1, 100
        READ(55,*) II, JJ, (ALHS(J,I), J= 1, 5)
      END DO
C
C LOOP ON FLANGE TEMPERATURE
C
   10 DO I=2,12
       TF = T(I)
C
C  LOOP ON PRESSURE 5 PSIG INCREMENTS
C
   20  DO J = 50, 280, 5
        PRES = J
C
C  LOOP ON LHS SAMPLE
C
   30    DO K =1,100
          KF = 6.28*R*THICK*EF(I)/L
          IF(TF.LT.600.0) THEN
          DT= ALHS(1,K)
          F = ALHS(3,K)*1E3
          S = ALHS(4,K)*1E-3
          ELSE
          DT = ALHS(2,K)
          F  = ALHS(3,K)*1E3
          S  = ALHS(5,K)*1E-3
          END IF
          TB = TF-DT
C
C INTERPOLATE MATERIAL PROPERTIES FOR BOLT AS NECESSARY
C
```

```
 40       DO II = 1,12
            IF(TB.LE.T(II)) THEN
            I1=II-1
            I2=II
            COEF1 = (T(I2)-TB)/(T(I2)-T(I1))
            COEF2 = (TB-T(I1))/(T(I2)-T(I1))
            EBI = COEF1*EB(I1) + COEF2*EB(I2)
            EBTI = COEF1*EBT(I1) [illegible]F2*EBT(I2)
            DELTAEPS = EPSF(I) - (COE[illegible] +
                       COEF2*EPS (I2))
            SIGMAY = 1000.*(COEF[illegible]*SIGY(I2))
            KBE = N*A*EBI/L
            KBT = N*A*EBTI/L
            MULT1 = KBE/(3.14*R**2)
            MULT2 = 1 + 2*NU*KBE/KF
            MULT3 = (KBE+KF)/(KBE*KF*MULT2)
            MULT4 = KBT/(3.14*R**2)
            YPRES = (N*SIGMAY*A)/(3.14*R**2)
            END IF
          END DO
C
C  CALCULATE LEAK AREA AS A FUNCTION OF PRESS FOR VARIOUS VALUES
C  OF DT, F, AND S
C
        IF(PRES.LE.YPRES) THEN
          Z1 = PRES/MULT1
        ELSE
          Z1 = YPRES/MULT1 + (PRES-YPRES)/MULT4
        END IF
        Z2 = MULT3*F
        Z3 = (DELTAEPS*L)/MULT2
        LA = (6.28*R)*(Z1 - Z2 - Z3 - S)
C
C  IF THE LEAK AREA IS LESS THAN ZERO THEN SET TO ZERO
C
        IF(LA.LE.0.) LA = 0
C
C WRITE THE VARIABLES TF, PRES, LA
C
 60     WRITE(20,*) TF, PRES, LA
       END DO
       END DO
       END DO
       STOP
      END
```

The result of running this program is a set of tables for each pressure giving, for different temperatures, the cumulative distribution for leak areas. For the case of an unsaturated pool a leak is < 4 in.^{2}; for a saturated pool a leak is less than 255 sq in. From these program output tables, we can construct tables for a particular temperature showing the cumulative probability of failure by pressure i and the conditional probability of leak versus rupture. However, the expert said that the process by which failure occurs is that the area will increase to the point that it just releases the pressure and is, therefore, always a leak. So only the cumulative failure probability was used with all failures assessed as leaks except in the 1200°F case when the failure pressure exceeded the yield strength.

	At 400°F	At 800°F	At 1200°F		
Pressure	Cum. Fail.	Cum. Fail.	Cum. Fail.	Leak	Rupture
50	0.0	0.0	0.03	1.0	0.0
55	0.0	0.01	0.05	1.0	0.0
60	0.0	0.03	0.09	1.0	0.0
65	0.0	0.03	0.12	1.0	0.0
70	0.0	0.04	0.14	1.0	0.0
75	0.0	0.07	0.15	1.0	0.0
80	0.0	0.09	0.18	1.0	0.0
85	0.0	0.12	0.21	1.0	0.0
90	0.0	0.14	0.24	1.0	0.0
95	0.0	0.15	0.32	1.0	0.0
100	0.0	0.18	0.42	1.0	0.0
105	0.01	0.21	0.46	0.93	0.07
110	0.01	0.24	0.56	0.84	0.16
115	0.01	0.25	0.65	0.80	0.20
120	0.01	0.30	0.70	0.35	0.65
125	0.02	0.38	0.79	0.63	0.37
130	0.04	0.46	0.84	0.37	0.63
135	0.05	0.52	0.90	0.23	0.77
140	0.09	0.60	0.95	0.11	0.89
145	0.13	0.65	0.98	0.05	0.95
150	0.15	0.70	1.0	0.0	1.0
155	0.19	0.75			
160	0.32	0.81			
165	0.37	0.85			
170	0.43	0.90			
175	0.48	0.95			
180	0.53	0.97			
185	0.59	0.98			
190	0.63	0.98			
195	0.67	1.0			
200	0.73	1.0			
205	0.77	1.0			

	At 400°F	At 800°F	At 1200°F		
Pressure	Cum. Fail.	Cum. Fail.	Cum. Fail	Leak	Rupture
210	0.81	1.0	-	-	-
215	0.83	1.0	-	-	-
220	0.84	1.0	-	-	-
225	0.88	1.0	-	-	-
230	0.91	1.0	-	-	-
235	0.92	1.0	-	-	-
240	0.92	1.0	-	-	-
245	0.93	1.0	-	-	-
250	0.93	1.0	-	-	-
255	0.95	1.0	-	-	-
260	0.96	1.0	-	-	-

The Expert C said that unless the maximum pressure exceeded the yield pressure that the leak area would decrease if the pressure decreased.

In order to calculate the total cumulative failure probability curve and the conditional probabilities, the same method was used as for Expert A. The three curves for wetwell, drywell, and drywell head were combined and conditionals calculated. The wetwell conditional was split in proportion to the splits given by the expert. For Case 4, the expert's results imply that no additional failure will occur since at least 50 psig is needed to get failure and, in this case, the pressure will be near atmospheric.

Tables C-1 through C-9 contain the results of Expert C's elicitation.

Table C-1

Results of Expert C: Cases 1 and 2

Pressure (psig)	Cumulative Failure Probability	Conditional Probability of Failure in Mode I at Pressure J									
		WWLaW	WWLbW	WWRaW	WWRbW	CWWR	DWL	DWRL	DWR	DWRR	CIWR
90.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
95.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
100.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
105.0000	0.0100	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
110.0000	0.0125	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
115.0000	0.0150	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
120.0000	0.0175	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
125.0000	0.0200	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
130.0000	0.0432	0.1243	0.0138	0.0000	0.0000	0.0000	0.0000	0.8618	0.0000	0.0000	0.0000
135.0000	0.0564	0.2214	0.0246	0.0000	0.0000	0.0000	0.0000	0.7540	0.0000	0.0000	0.0000
140.0000	0.0991	0.0646	0.0072	0.0000	0.0000	0.0000	0.0000	0.9282	0.0000	0.0000	0.0000
145.0000	0.2468	0.6398	0.0717	0.0075	0.0296	0.0000	0.0000	0.2512	0.0000	0.0000	0.0000
150.0000	0.3697	0.7030	0.0796	0.0173	0.0693	0.0000	0.0000	0.1308	0.0000	0.0000	0.0000
155.0000	0.5312	0.3798	0.0431	0.0238	0.1717	0.0000	0.0000	0.1632	0.2184	0.0000	0.0000
160.0000	0.7064	0.2008	0.0229	0.0273	0.2274	0.0000	0.0000	0.3739	0.1478	0.0000	0.0000
165.0000	0.8110	0.1478	0.0170	0.0497	0.4421	0.0000	0.0000	0.1742	0.1691	0.0000	0.0000
170.0000	0.9608	0.0767	0.0092	0.0393	0.7428	0.0000	0.0000	0.0722	0.0578	0.0000	0.0000
175.0000	0.9828	0.0703	0.0082	0.0176	0.6814	0.0000	0.0000	0.1142	0.1082	0.0000	0.0000
180.0000	0.9987	0.0808	0.0094	0.0000	0.8039	0.0000	0.0000	0.0545	0.0514	0.0000	0.0000
185.0000	0.9990	0.0179	0.0021	0.0000	0.1908	0.0000	0.0000	0.4454	0.3438	0.0000	0.0000
190.0000	0.9993	0.0189	0.0022	0.0000	0.2174	0.0000	0.0000	0.3547	0.4068	0.0000	0.0000
195.0000	0.9994	0.0227	0.0026	0.0000	0.2838	0.0000	0.0000	0.4779	0.2140	0.0000	0.0000
200.0000	0.9996	0.0162	0.0019	0.0000	0.2214	0.0000	0.0000	0.5987	0.1618	0.0000	0.0000
205.0000	0.9997	0.0178	0.0021	0.0000	0.2661	0.0000	0.0000	0.5261	0.1879	0.0000	0.0000
210.0000	0.9998	0.0155	0.0018	0.0000	0.2577	0.0000	0.0000	0.5500	0.1750	0.0000	0.0000
215.0000	0.9998	0.0191	0.0022	0.0000	0.3535	0.0000	0.0000	0.3956	0.2297	0.0000	0.0000
220.0000	0.9999	0.0215	0.0025	0.0000	0.4519	0.0000	0.0000	0.2452	0.2790	0.0000	0.0000
225.0000	0.9999	0.0107	0.0012	0.0000	0.2585	0.0000	0.0000	0.5794	0.1502	0.0000	0.0000
230.0000	1.0000	0.0100	0.0012	0.0000	0.2849	0.0000	0.0000	0.5498	0.1540	0.0000	0.0000
235.0000	1.0000	0.0142	0.0016	0.0000	0.4867	0.0000	0.0000	0.2571	0.2403	0.0000	0.0000
240.0000	1.0000	0.0120	0.0014	0.0000	0.5157	0.0000	0.0000	0.2442	0.2267	0.0000	0.0000
245.0000	1.0000	0.0083	0.0010	0.0000	0.4816	0.0000	0.0000	0.1964	0.3127	0.0000	0.0000
250.0000	1.0000	0.0060	0.0007	0.0000	0.5260	0.0000	0.0000	0.1718	0.2955	0.0000	0.0000
255.0000	1.0000	0.0034	0.0004	0.0000	0.6013	0.0000	0.0000	0.1346	0.2597	0.0000	0.0000
260.0000	1.0000	0.0030	0.0000	0.0000	0.6887	0.0000	0.0000	0.1311	0.2002	0.0000	0.0000
265.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3003	0.6987	0.0000	0.0000
270.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.4000	0.6000	0.0000	0.0000
275.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000

Table C-2
Expert C: Cases 1 and 2 Data Conversion

Pressure (psig)	Independent Cumulative Failure Probability for Initial Modes			Cond. Probability of Wetwell Modes Given Wetwell Failure			
	DWR	DWHL	HW	WWLaW	WWLbW	WWRaW	WWRbW
100.0000	0.0000	0.0000	0.0000	0.9000	0.1000	0.0000	0.0000
105.0000	0.0000	0.0100	0.0000	0.9000	0.1000	0.0000	0.0000
110.0000	0.0000	0.0125	0.0000	0.9000	0.1000	0.0000	0.0000
115.0000	0.0000	0.0150	0.0000	0.9000	0.1000	0.0000	0.0000
120.0000	0.0000	0.0175	0.0000	0.9000	0.1000	0.0000	0.0000
125.0000	0.0000	0.0200	0.0000	0.9000	0.1000	0.0000	0.0000
130.0000	0.0000	0.0400	0.0032	0.9000	0.1000	0.0000	0.0000
135.0000	0.0000	0.0500	0.0067	0.9000	0.1000	0.0000	0.0000
140.0000	0.0000	0.0900	0.0100	0.9000	0.1000	0.0000	0.0000
145.0000	0.0000	0.1300	0.1343	0.8544	0.0958	0.0100	0.0398
150.0000	0.0000	0.1500	0.2585	0.8088	0.0916	0.0199	0.0797
155.0000	0.0625	0.1900	0.3828	0.6142	0.0697	0.0385	0.2776
160.0000	0.1250	0.3200	0.5066	0.4197	0.0478	0.0571	0.4754
165.0000	0.1875	0.3700	0.6307	0.2251	0.0259	0.0757	0.6733
170.0000	0.2500	0.4300	0.9084	0.0904	0.0107	0.0452	0.8537
175.0000	0.3125	0.4800	0.9520	0.0904	0.0106	0.0226	0.8764
180.0000	0.3750	0.5300	0.99[illegible]	0.0904	0.0105	0.0000	0.8991
185.0000	0.4375	0.5900	0.9958	0.0847	0.0098	0.0000	0.9054
190.0000	0.5000	0.6300	0.9961	0.0791	0.009[illegible]	0.0000	0.9117
195.0000	0.5250	0.6700	0.9963	0.0734	0.0085	0.0000	0.9180
200.0000	0.5500	0.7300	0.9966	0.0678	0.0079	0.0000	0.9243
205.0000	0.5750	0.7700	0.9969	0.0621	0.0072	0.0000	0.9306
210.0000	0.6000	0.8100	0.9972	0.0565	0.006[illegible]	0.0000	0.9369
215.0000	0.6250	0.8300	0.9975	0.0508	0.0059	0.0000	0.9432
220.0000	0.6500	0.8400	0.9978	0.0452	0.0052	0.0000	0.9495
225.0000	0.6750	0.8800	0.9980	0.0395	0.0046	0.0000	0.9559
230.0000	0.7000	0.9100	0.9983	0.0339	0.003[illegible]	0.0000	0.9622
235.0000	0.7250	0.9180	0.9986	0.0282	0.0033	0.0000	0.9685
240.0000	0.7500	0.9260	0.9989	0.0226	0.0026	0.0000	0.9748
245.0000	0.7917	0.9340	0.9992	0.0169	0.0020	0.0000	0.9811
250.0000	0.8333	0.9420	0.9994	0.0113	0.0013	0.0000	0.9874
255.0000	0.8750	0.9500	0.9997	0.0056	0.0007	0.0000	0.9937
260.0000	0.9167	0.9600	1.0000	0.0000	0.0000	0.0000	1.0000
265.0000	0.9583	0.9700	1.0000	0.0000	0.0000	0.0000	1.0000
270.0000	0.9792	0.9800	1.0000	0.0000	0.0000	0.0000	1.0000
275.0000	1.0000	0.9900	1.0000	0.0000	0.0000	0.0000	1.0000

Table C-3

Expert C'S Conditional Probabilities: Cases 1 & 2

Pressure (psig)	Conditional Probability of Failure			Normalized Conditional Probability of Failures*			Conditional Probability for Wetwell Modes				Cumulative Failure	Cumulative Failure
	DWR	DWSL	WW	DWR	DWSL	WW	WWLaW	WWLbW	WWRaW	WWRbW	All Modes	DWR,DWSL
100.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
105.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0100	0.0100
110.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0125	0.0125
115.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0150	0.0150
120.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0175	0.0175
125.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0200	0.0200
130.0000	0.0000	0.8618	0.1382	0.0000	0.8618	0.1382	0.1243	0.0138	0.0000	0.0000	0.0432	0.0400
135.0000	0.0000	0.7540	0.2460	0.0000	0.7540	0.2460	0.2214	0.0246	0.0000	0.0000	0.0564	0.0500
140.0000	0.0000	0.9282	0.0718	0.0000	0.9282	0.0718	0.0646	0.0072	0.0000	0.0000	0.0991	0.0900
145.0000	0.0000	0.2516	0.7499	0.0000	0.2512	0.7488	0.6398	0.0717	0.0075	0.0298	0.2468	0.1300
150.0000	0.0000	0.1309	0.8700	0.0000	0.1308	0.8692	0.7077	0.0796	0.0173	0.0693	0.3687	0.1500
155.0000	0.2196	0.1641	0.6218	0.2184	0.1632	0.6184	0.3738	0.0431	0.0235	0.1717	0.5312	0.2406
160.0000	0.1500	0.3795	0.4856	0.1478	0.3739	0.4784	0.2008	0.0229	0.0273	0.2274	0.7064	0.4050
165.0000	0.1710	0.1762	0.6641	0.1691	0.1742	0.6567	0.1478	0.0170	0.0487	0.4421	0.8110	0.4881
170.0000	0.0609	0.0761	0.9174	0.0578	0.0722	0.8700	0.0787	0.0093	0.0393	0.7428	0.9608	0.5725
175.0000	0.1113	0.1174	0.7996	0.1082	0.1142	0.7776	0.0703	0.0082	0.0176	0.6814	0.9828	0.6425
180.0000	0.0556	0.0589	0.9669	0.0514	0.0545	0.8941	0.0806	0.0094	0.0000	0.8039	0.9987	0.7063
185.0000	0.3461	0.4484	0.2122	0.3433	0.4454	0.2107	0.0179	0.0021	0.0000	0.1908	0.9990	0.7694
190.0000	0.4093	0.3568	0.2398	0.4066	0.3547	0.2385	0.0189	0.0022	0.0000	0.2174	0.9993	0.8150
195.0000	0.2149	0.4788	0.3104	0.2140	0.4769	0.3091	0.0227	0.0026	0.0000	0.2838	0.9994	0.8433
200.0000	0.1630	0.6030	0.2412	0.1618	0.5987	0.2395	0.0162	0.0019	0.0000	0.2214	0.9996	0.8785
205.0000	0.1891	0.5295	0.2878	0.1879	0.5261	0.2859	0.0178	0.0021	0.0000	0.2661	0.9997	0.9023
210.0000	0.1764	0.5544	0.2772	0.1750	0.5500	0.2750	0.0155	0.0018	0.0000	0.2577	0.9998	0.9240
215.0000	0.2310	0.3978	0.3769	0.2297	0.3956	0.3747	0.0181	0.0022	0.0000	0.3535	0.9998	0.9363
220.0000	0.2802	0.2462	0.4780	0.2790	0.2452	0.4756	0.0215	0.0025	0.0000	0.4518	0.9999	0.9440
225.0000	0.1526	0.5886	0.2747	0.1502	0.5794	0.2704	0.0107	0.0012	0.0000	0.2585	0.9999	0.9610
230.0000	0.1568	0.5598	0.3015	0.1540	0.5499	0.2951	0.0100	0.0012	0.0000	0.2849	1.0000	0.9730
235.0000	0.2426	0.2595	0.5072	0.2403	0.2571	0.5025	0.0142	0.0016	0.0000	0.4867	1.0000	0.9775
240.0000	0.2295	0.2471	0.5355	0.2267	0.2442	0.5291	0.0120	0.0014	0.0000	0.5157	1.0000	0.9815
245.0000	0.3201	0.2010	0.5026	0.3127	0.1964	0.4909	0.0083	0.0010	0.0000	0.4815	1.0000	0.9853
250.0000	0.3068	0.1784	0.5531	0.2955	0.1718	0.5327	0.0060	0.0007	0.0000	0.5260	1.0000	0.9903
255.0000	0.2795	0.1448	0.6517	0.2597	0.1346	0.6057	0.0034	0.0004	0.0000	0.6018	1.0000	0.9938
260.0000	0.2002	0.1111	0.6887	0.2002	0.1111	0.6887	0.0000	0.0000	0.0000	0.6887	1.0000	0.9967
265.0000	0.7329	0.3145	0.0000	0.6997	0.3003	0.0000	0.0000	0.0000	0.0000	0.0300	1.0000	0.9987
270.0000	0.6000	0.4000	0.0000	0.6000	0.4000	0.0000	0.0000	0.0007	0.0000	0.0000	1.0000	0.9996
275.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000

*Due to small errors, the conditional probabilities calculated did not sum precisely to 1.0; therefore, normalized by sum.

Table C-4
Results of Expert C: Case 3A and 2

Pressure (psig)	Cumulative Failure Probability	Conditional Probability of Failure in Mode I at Pressure J									
		WWLaW	WWLbW	WWRaW	WWRbW	CWWR	DWL	DWWL	DWR	DWWR	CDWR
50.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
55.0000	0.0100	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
60.0000	0.0299	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
65.0000	0.0310	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
70.0000	0.0400	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
75.0000	0.0700	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
80.0000	0.0900	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
85.0000	0.1200	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
90.0000	0.1400	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
95.0000	0.1500	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
100.0000	0.1800	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
105.0000	0.2100	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
110.0000	0.3033	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3080	0.6920	0.0000	0.0000
115.0000	0.3750	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1221	0.8779	0.0000	0.0000
120.0000	0.4750	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3958	0.6042	0.0000	0.0000
125.0000	0.5505	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.7815	0.2185	0.0000	0.0000
130.0000	0.6220	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.7972	0.2028	0.0000	0.0000
135.0000	0.6760	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.7639	0.2361	0.0000	0.0000
140.0000	0.7426	0.0394	0.0044	0.0000	0.0000	0.0000	0.0000	0.7919	0.1644	0.0000	0.0000
145.0000	0.8106	0.3733	0.0419	0.0044	0.0174	0.0000	0.0000	0.4351	0.1280	0.0000	0.0000
150.0000	0.8665	0.3580	0.0405	0.0088	0.0353	0.0000	0.0000	0.4405	0.1169	0.0000	0.0000
155.0000	0.9112	0.2756	0.0313	0.0173	0.1246	0.0000	0.0000	0.4468	0.1046	0.0000	0.0000
160.0000	0.9484	0.1734	0.0198	0.0236	0.1965	0.0000	0.0000	0.3045	0.0822	0.0000	0.0000
165.0000	0.9709	0.1137	0.0131	0.0382	0.3401	0.0000	0.0000	0.4132	0.0817	0.0000	0.0000
170.0000	0.9954	0.0659	0.0078	0.0329	0.6220	0.0000	0.0000	0.2419	0.0295	0.0000	0.0000
175.0000	0.9989	0.0403	0.0048	0.0102	0.3969	0.0000	0.0000	0.4840	0.0631	0.0000	0.0000
180.0000	0.9999	0.0665	0.0077	0.0000	0.6615	0.0000	0.0000	0.2220	0.0423	0.0000	0.0000
185.0000	1.0000	0.0105	0.0012	0.0000	0.1117	0.0000	0.0000	0.6752	0.2014	0.0000	0.0000
190.0000	1.0000	0.0190	0.0022	0.0000	0.2194	0.0000	0.0000	0.3489	0.4105	0.0000	0.0000
195.0000	1.0000	0.0027	0.0003	0.0000	0.0340	0.0000	0.0000	0.8963	0.0667	0.0000	0.0000
200.0000	1.0000	0.0222	0.0027	0.0000	0.3162	0.0000	0.0000	0.0000	0.6579	0.0000	0.0000
205.0000	1.0000	0.0175	0.0020	0.0000	0.2617	0.0000	0.0000	0.0000	0.7187	0.0000	0.0000
210.0000	1.0000	0.0141	0.0016	0.0000	0.2342	0.0000	0.0000	0.0000	0.7500	0.0000	0.0000
215.0000	1.0000	0.0106	0.0012	0.0000	0.1965	0.0000	0.0000	0.0000	0.7917	0.0000	0.0000
220.0000	1.0000	0.0068	0.0008	0.0000	0.1424	0.0000	0.0000	0.0000	0.8500	0.0000	0.0000
225.0000	1.0000	0.0026	0.0003	0.0000	0.0637	0.0000	0.0000	0.0000	0.9333	0.0000	0.0000

Table C-5
Expert C: Case 3A Data Conversion

Pressure (psig)	Independent Cumulative Failure Probability for Initial Modes			Cond. Probability of Wetwell Modes Given Wetwell Failure				Cumulative Failure: All Modes
	DWR	DWRL	WW	WWLaW	WWLbW	WWRaW	WWRbW	
50.0000	0.0000	0.0000	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000
55.0000	0.0000	0.0100	0.0000	0.9000	0.1000	0.0000	0.0000	0.0100
60.0000	0.0000	0.0299	0.0000	0.9000	0.1000	0.0000	0.0000	0.0299
65.0000	0.0000	0.0310	0.0000	0.9000	0.1000	0.0000	0.0000	0.0310
70.0000	0.0000	0.0400	0.0000	0.9000	0.1000	0.0000	0.0000	0.0400
75.0000	0.0000	0.0700	0.0000	0.9000	0.1000	0.0000	0.0000	0.0700
80.0000	0.0000	0.0900	0.0000	0.9000	0.1000	0.0000	0.0000	0.0900
85.0000	0.0000	0.1200	0.0000	0.9000	0.1000	0.0000	0.0000	0.1200
90.0000	0.0000	0.1400	0.0000	0.9000	0.1000	0.0000	0.0000	0.1400
95.0000	0.0000	0.1500	0.0000	0.9000	0.1000	0.0000	0.0000	0.1500
100.0000	0.0000	0.1800	0.0000	0.9000	0.1000	0.0000	0.0000	0.1800
105.0000	0.0000	0.2100	0.0000	0.9000	0.1000	0.0000	0.0000	0.2100
110.0000	0.0833	0.2400	0.0000	0.9000	0.1000	0.0000	0.0000	0.3033
115.0000	0.1667	0.2500	0.0000	0.9000	0.1000	0.0000	0.0000	0.3750
120.0000	0.2500	0.3000	0.0000	0.9000	0.1000	0.0000	0.0000	0.4750
125.0000	0.2750	0.3800	0.0000	0.9000	0.1000	0.0000	0.0000	0.5505
130.0000	0.3000	0.4600	0.0000	0.9000	0.1000	0.0000	0.0000	0.6220
135.0000	0.3250	0.5200	0.0000	0.9000	0.1000	0.0000	0.0000	0.6760
140.0000	0.3500	0.6000	0.0100	0.9000	0.1000	0.0000	0.0000	0.7426
145.0000	0.3750	0.6500	0.1343	0.8544	0.0958	0.0100	0.0398	0.[illegible]106
150.0000	0.4000	0.7000	0.2585	0.8088	0.0916	0.0199	0.0797	0.8665
155.0000	0.4250	0.7500	0.3826	0.6142	0.0687	0.0385	0.2776	0.9112
160.0000	0.4500	0.8100	0.5066	0.4197	0.0478	0.0571	0.4754	0.9484
165.0000	0.4750	0.8500	0.6307	0.2251	0.0259	0.0757	0.6733	0.9709
170.0000	0.5000	0.9000	0.9084	0.0904	0.0107	0.0452	0.8537	0.9954
175.0000	0.5417	0.9500	0.9520	0.0904	0.0106	0.0226	0.8764	0.9989
180.0000	0.5833	0.9700	0.9955	0.0904	0.0105	0.0000	0.8991	0.9999
185.0000	0.6250	0.9790	0.9958	0.0847	0.0098	0.0000	0.9054	1.0000
190.0000	0.6667	0.9810	0.9961	0.0791	0.0092	0.0000	0.9117	1.0000
195.0000	0.7083	1.0000	0.9963	0.0734	0.0085	0.0000	0.9180	1.0000
200.0000	0.7500	1.0000	0.9966	0.0678	0.0079	0.0000	0.9243	1.0000
205.0000	0.8000	1.0000	0.9969	0.0621	0.0072	0.0000	0.9306	1.0000
210.0000	0.8500	1.0000	0.9972	0.0565	0.0066	0.0000	0.9369	1.0000
215.0000	0.9000	1.0000	0.9975	0.0508	0.0059	0.0000	0.9432	1.0000
220.0000	0.9500	1.0000	0.9978	0.0452	0.0052	0.0000	0.9495	1.0000
225.0000	1.0000	1.0000	0.9980	0.0395	0.0046	0.0000	0.9559	1.0000

Table C-6

Expert C's Conditional Probabilities: Case 3A

Pressure (psig)	Cum.Fail DWR & WW Modes Only	Conditional Probability of Failure			Normalized Conditional Probability of Failures*			Conditional Probability for Wetwell Modes			
		DWR	DWRL	WW	DWR	DWRL	WW	WWLaW	WWLbW	WWRaW	WWRbW
50.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
55.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
60.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
65.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
70.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
75.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
80.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
85.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
90.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
95.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
100.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
105.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
110.0000	0.0833	0.6925	0.3083	0.0000	0.6920	0.3080	0.0000	0.0000	0.0000	0.0000	0.0000
115.0000	0.1667	0.8782	0.1221	0.0000	0.8779	0.1221	0.0000	0.0000	0.0000	0.0000	0.0000
120.0000	0.2500	0.6053	0.3966	0.0000	0.6042	0.3958	0.0000	0.0000	0.0000	0.0000	0.0000
125.0000	0.2750	0.2188	0.7823	0.0000	0.2185	0.7815	0.0000	0.0000	0.0000	0.0000	0.0000
130.0000	0.3000	0.2030	0.7982	0.0000	0.2028	0.7972	0.0000	0.0000	0.0000	0.0000	0.0000
135.0000	0.3250	0.2364	0.7647	0.0000	0.2361	0.7639	0.0000	0.0000	0.0000	0.0000	0.0000
140.0000	0.3565	[illegible]547	0.7936	0.0439	0.1644	0.7919	0.0438	0.0394	0.0044	0.0000	0.0000
145.0000	0.4589	0.[illegible]288	0.4379	0.4398	0.1280	0.4351	0.4370	0.3733	0.0419	0.0044	0.0174
150.0000	0.5551	0.1178	0.4442	0.4464	0.1169	0.4405	0.4427	0.3580	0.0405	0.0088	0.0353
155.0000	0.6450	0.1057	0.4518	0.4537	0.1046	0.4466	0.4487	0.2756	0.0313	0.0173	0.1246
160.0000	0.7286	0.0838	0.5144	0.4213	0.0822	0.5045	0.4132	0.1734	0.0198	0.0236	0.1965
165.0000	0.8061	0.0834	0.4221	0.5160	0.0817	0.4132	0.5051	0.1137	0.0131	0.0382	0.3401
170.0000	0.9542	0.0335	0.2748	0.8278	0.0295	0.2419	0.7286	0.0659	0.0078	0.0329	0.6220
175.0000	0.9780	0.0710	0.5444	0.5093	0.0631	0.4840	0.4528	0.0409	0.0048	0.0102	0.3969
180.0000	0.9981	0.0527	0.2769	0.9180	0.0423	0.2220	0.7358	0.0665	0.0077	0.0000	0.6615
185.0000	0.9984	0.2045	0.6857	0.1253	0.2014	0.6752	0.1234	0.0105	0.0012	0.0000	0.1117
190.0000	0.9987	0.4129	0.3510	0.2421	0.4105	0.3489	0.2406	0.0190	0.0022	0.0000	0.2194
195.0000	0.9989	0.0667	0.8963	0.0370	0.0567	0.8963	0.0370	0.0027	0.000[illegible]	0.0000	0.0340
200.0000	0.9992	0.6599	0.0000	0.3432	0.6579	0.0000	0.3421	0.0232	0.0027	0.0000	0.3162
205.0000	0.9994	0.7222	0.0000	0.2826	0.7187	0.0000	0.2813	0.0175	0.0020	0.0006	0.2617
210.0000	0.9996	0.7551	0.0000	0.2517	0.7500	0.0000	0.2500	0.0141	0.0016	0.0000	0.2342
215.0000	0.9997	0.8000	0.0000	0.2105	0.7917	0.0000	0.2083	0.0106	0.0012	0.0000	0.1965
220.0000	0.9999	0.8667	0.0000	0.1529	0.8500	0.0000	0.1500	0.0068	0.0008	0.0000	0.1424
225.0000	1.0000	0.9333	0.0000	0.0667	0.9333	0.0000	0.0667	0.0026	0.0003	0.0000	0.0637

*Due to small errors, the conditional probabilities calculated did not sum precisely to 1.0; therefore, normalized by sum.

Table C-7
Results of Expert C: Case 3B and 2

Pressure (psig)	Cumulative Failure Probability	Conditional Probability of Failure in Mode I at Pressure J									
		WWLaW	WWLbW	WWRaW	WWRbW	CWWR	DWL	DWRL	DWR	DWSR	CDWR
5.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
10.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
15.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
20.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
25.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
30.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
35.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
40.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
45.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
50.0000	0.0300	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
55.0000	0.0500	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
60.0000	0.3175	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1308	0.8692	0.0000	0.0000
65.0000	0.7067	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0418	0.9582	0.0000	0.0000
70.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0115	0.9885	0.0000	0.0000
75.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
80.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
85.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
90.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
95.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
100.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
105.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9300	0.0000	0.0700	0.0000
110.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.8400	0.0000	0.1600	0.0000
115.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.8000	0.0000	0.2000	0.0000
120.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3500	0.0000	0.6500	0.0000
125.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6300	0.0000	0.3700	0.0000
130.0000	1.0000	0.0110	0.0012	0.0000	0.0000	0.0000	0.0000	0.3655	0.0000	0.6223	0.0000
135.0000	1.0000	0.0065	0.0007	0.0000	0.0000	0.0000	0.0000	0.2283	0.0000	0.7645	0.0000
140.0000	1.0000	0.0045	0.0005	0.0000	0.0000	0.0000	0.0000	0.1094	0.0000	0.8855	0.0000
145.0000	1.0000	0.1154	0.0129	0.0014	0.0054	0.0000	0.0000	0.0432	0.0000	0.8216	0.0000
150.0000	1.0000	0.0625	0.0071	0.0015	0.0062	0.0000	0.0000	0.0000	0.0000	0.9227	0.0000
155.0000	1.0000	0.6142	0.0697	0.0385	0.2776	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
160.0000	1.0000	0.4197	0.0478	0.0571	0.4754	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
165.0000	1.0000	0.2251	0.0259	0.0757	0.6733	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
170.0000	1.0000	0.0904	0.0107	0.0452	0.8537	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
175.0000	1.0000	0.0904	0.0106	0.0226	0.8764	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
180.0000	1.0000	0.0904	0.0105	0.0000	0.8991	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table C-8
Expert C: Case 3B Data Conversion

Pressure (psia)	Independent Cumulative Failure Probability for Initial Modes			Conditional Probability of Wetwell Modes Given Wetwell Failure				Conditional Probability of Failure			Cum. Fail. All Modes	Cum. Fail. DWHL\R and WW Only
	DWR	DWHL\R	WW	WWLaW	WWLbW	WWRaW	WWRbW	DWR	DWHL	WW		
5.0000	0.0000	0.0000	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
10.0000	0.0000	0.0000	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
15.0000	0.0000	0.0000	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
20.0000	0.0000	0.0000	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
25.0000	0.0000	0.0000	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
30.0000	0.0000	0.0000	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
35.0000	0.0000	0.0000	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
40.0000	0.0000	0.0000	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
45.0000	0.0000	0.0000	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
50.0000	0.0000	0.0300	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0300	0.0300
55.0000	0.0000	0.0500	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0500	0.0500
60.0000	0.2500	0.0900	0.0000	0.9000	0.1000	0.0000	0.0000	0.87[illegible]	0.1312	0.0000	0.3175	0.0900
65.0000	0.6667	0.1200	0.0000	0.9000	0.1000	0.0000	0.0000	0.96[illegible]	0.0420	0.0000	0.7067	0.1200
70.0000	1.0000	0.1400	0.0000	0.9000	0.1000	0.0000	0.0000	0.9885	0.0115	0.0000	1.0000	0.1400
75.0000	1.0000	0.1500	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.1500
80.0000	1.0000	0.1800	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.1800
85.0000	1.0000	0.2100	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.2100
90.0000	1.0000	0.2400	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.2400
95.0000	1.0000	0.3200	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.3200
100.0000	1.0000	0.4200	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.4200
105.0000	1.0000	0.4600	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.4600
110.0000	1.0000	0.5600	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.5600
115.0000	1.0000	0.6500	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.6500
120.0000	1.0000	0.7000	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.7000
125.0000	1.0000	0.7900	0.0000	0.9000	0.1000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.7900
130.0000	1.0000	0.8400	0.0033	0.9000	0.1000	0.0000	0.0000	0.0000	0.9880	0.0122	1.0000	0.8405
135.0000	1.0000	0.9000	0.0067	0.9000	0.1000	0.0000	0.0000	0.0000	0.9932	0.0072	1.0000	0.9007
140.0000	1.0000	0.9500	0.0100	0.9000	0.1000	0.0000	0.0000	0.0000	0.9955	0.0050	1.0000	0.9505
145.0000	1.0000	0.9800	0.1343	0.8544	0.0958	0.0100	0.0398	0.0000	0.8897	0.1390	1.0000	0.9827
150.0000	1.0000	1.0000	0.2585	0.8086	0.0916	0.0199	0.0797	0.0000	0.9227	0.0773	1.0000	1.0000
155.0000	1.0000	1.0000	0.3817	0.6142	0.0697	0.0385	0.2776	0.0000	0.0000	1.0000	1.0000	1.0000
160.0000	1.0000	1.0000	0.5053	0.4197	0.0478	0.0571	0.4754	0.0000	0.0000	1.0000	1.0000	1.0000
165.0000	1.0000	1.0000	0.6307	0.2251	0.0259	0.0757	0.6733	0.0000	0.0000	1.0000	1.0000	1.0000
170.0000	1.0000	1.0000	0.9084	0.0904	0.0107	0.0452	0.8537	0.0000	0.0000	1.0000	1.0000	1.0000
175.0000	1.0000	1.0000	0.9520	0.0904	0.0106	0.0226	0.8764	0.0000	0.0000	1.0000	1.0000	1.0000
180.0000	1.0000	1.0000	0.9955	0.0904	0.0105	0.0000	0.8991	0.0000	0.0000	1.0000	1.0000	1.0000

Table C-9

Expert C's Conditional Probabilities: Case 3B

Pressure (psig)	Normalized Conditional Probability of Failures*			Conditional Probability for Wetwell Modes				Conditional Split for DWRL\R			
	DWR	DWRL	WW	WWLaW	WWLbW	WWRaW	WWRbW	L	R	DWRL	DWRR
5.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
10.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
15.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
20.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
25.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
30.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
35.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
40.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
45.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
50.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
55.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
60.0000	0.8692	0.1308	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.1308	0.0000
65.0000	0.9582	0.0418	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0418	0.0000
70.0000	0.9885	0.0115	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0115	0.0000
75.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
80.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
85.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
90.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
95.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
100.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000
105.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9300	0.0700	0.9300	0.0700
110.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.8400	0.1600	0.8400	0.1600
115.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.8000	0.2000	0.8000	0.2000
120.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3500	0.6500	0.3500	0.6500
125.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6300	0.3700	0.6300	0.3700
130.0000	0.0000	0.9878	0.0122	0.0110	0.0012	0.0000	0.0000	0.3700	0.6300	0.3655	0.6223
135.0000	0.0000	0.9928	0.0072	0.0065	0.0007	0.0000	0.0000	0.2300	0.7700	0.2283	0.7645
140.0000	0.0000	0.9950	0.0050	0.0045	0.0005	0.0000	0.0000	0.1100	0.8900	0.1094	0.8855
145.0000	0.0000	0.8649	0.1351	0.1154	0.0129	0.0014	0.0054	0.0500	0.9500	0.0432	0.8216
150.0000	0.0000	0.9227	0.0773	0.0625	0.0071	0.0015	0.0062	0.0000	1.0000	0.0000	0.9227
155.0000	0.0000	0.0000	1.0000	0.6142	0.0697	0.0385	0.2776	0.0000	1.0000	0.0000	0.0000
160.0000	0.0000	0.0000	1.0000	0.4197	0.0478	0.0571	0.4754	0.0000	1.0000	0.0000	0.0000
165.0000	0.0000	0.0000	1.0000	0.2251	0.0259	0.0757	0.6733	0.0000	1.0000	0.0000	0.0000
170.0000	0.0000	0.0000	1.0000	0.0904	0.0107	0.0452	0.8537	0.0000	1.0000	0.0000	0.0000
175.0000	0.0000	0.0000	1.0000	0.0904	0.0106	0.0226	0.8764	0.0000	1.0000	0.0000	0.0000
180.0000	0.0000	0.0000	1.0000	0.0904	0.0105	0.0000	0.8991	0.0000	1.0000	0.0000	0.0000

*Due to small errors, the conditional probabilities calculated did not sum precisely to 1.0; therefore, normalized by sum.

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5.4. Issue 4. Effect of Wetwell Rupture on ECCS Survivability and Reactor Building Integrity at Peach Bottom

Experts consulted: David B. Clauss, Sandia National Laboratories; Ken Mohktarian, Chicago Bridge & Iron; Subir Sen, Bechtel Corporation.

Issue Description

This issue addresses two questions: (1) What is the probability of a containment rupture with enough kinetic energy to sever emergency core cooling system (ECCS) piping? and (2) What is the probability of significant reactor building bypass given a rupture in the wetwell at Peach Bottom?

This issue is very closely related to the P-T induced containment failure issue (Issue 3). The initial conditions for this issue are containment failure in the torus and a wetwell rupture (WWR) or a catastrophic rupture (CWWR) failure mode (see Issue 3). Whether containment failure breaks the ECCS lines is important in sequences in which the containment fails before the onset of core damage. Whether wetwell rupture leads to reactor building bypass is important in sequences in which core damage occurs before containment failure because a potential source of decontamination (the reactor building) could be eliminated.

There are three types of questions in the accident progression tree (APET) that are relevant to this issue:

Question Type 1: Is the suppression pool drained before core damage? The answers to this question characterize the state of the wetwell. There are three states: drainage: (a) suppression pool drained completely, representing a catastrophic wetwell failure; (b) suppression pool depleted so that the water level is below the drywell vents, representing a failure below the water level in the torus and; (c) no suppression pool drainage, the failure is above the water line and is not catastrophic.

Question Type 2: After the suppression pool drainage question, the status of the condensate system piping, the status of the control rod drive piping, and the status of the high pressure service water piping are asked. The piping in each of the systems is either intact or it is not. (Success or failure of these systems also depends on issues other than the one being considered.) The review group was asked to provide the probabilities of survivability of the lines for these three systems given a wetwell failure by rupture.

Question Type 3: What is the level of reactor building breach/bypass without a hydrogen burn? Four levels of bypass are considered: (a) no bypass--the standby gas treatment system can handle all releases to the reactor building, Question Type 3 Continued

(b) small level of bypass--most of the release passes through the reactor building, (c) large level of bypass--decontamination of the release is equivalent to decontamination of releases that have gone to the refueling bay, and (d) complete bypass of the reactor building. The review group was as.ed to provide the relative probabilities of the different levels of bypass given a wetwell failure.

Summary of Results

All three experts agreed that failure of the control rod drive (CRD) or condensate piping is negligible. They also ag: .d that only the unreinforced portions of the wetwell could fail catastrophically and that only catastrophic rupture could fail the piping high pressure service water (HPSW)--residual heat removal (RHR). There is additional structural reinforcement in the eight sections that contain the downcomers. Expert A said that the probability of the HPSW-RHR piping in the torus room failing was a simple ratio of the number of sections of the torus facing the piping to the total. This gives 4/8 = 0.50 for the probability of HPSW line pipe failure, since four of the eight unreinforced segments face the HPSW pipe. Expert B said that the piping failed only if fragments were generated and gave a 0.8 probability of fragments. This gives (4/8)*.8 = 0.40 for the probability of pipe failure. Expert C, gave a 0.12 conditional probability of pipe failure. Averaging these failure probabilities gives (.50 + .40 + .12)/3 = 0.34 for the aggregated conditional probability of pipe failure given a CWWR.

The following tables give the probability of each reactor building bypass level as given by each expert for the WWR case.

Table 4-1
Probability of Reactor Building Bypass for WWR--Expert A

Bypass Level	Pressure(psig) 0	.25	3	5	6	10	15	20	50
a	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
b	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
c	0.0	0.0	0.0	1.0	1.0	1.0	0.5	0.0	0.0
d	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	1.0

Values were linearly interpolated for the 6 psig case and linearly extrapolated for the 50 psig case. Level "a" goes to zero from 1.0 at .25.

Table 4-2
Probability of Reactor Building Bypass for WWR--Expert B

Bypass Level	Pressure (psig) 0	.25	3	5	6	10	15	20	50
a	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
b	0.0	1.0	1.0	1.0	1.0	0.75	0.575	0.40	0.0
c	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
d	0.0	0.0	0.0	0.0	0.0	0.25	0.425	0.60	1.0

Values were linearly interpolated for the 3, 5, and 15 psig cases.

Table 4-3
Failure Probabilities for Seven Cases for WWR--Expert C

Bypass Level	Cases 1	2	3	4	5	6	7
a	0.70	0.20	0.80	0.30	0.70	0.20	0.08
b	0.05	0.10	0.05	0.10	0.05	0.10	0 06
c	0.25	0.40	0.15	0.40	0.25	0.40	0.06
d	0.00	0.30	0.00	0.20	0.00	0.30	0.80
a+b	0.75	0.30	0.85	0.40	0.75	0.30	0.14

Since level "a" includes the blowout panels for this expert.

The cases for Table 3 were defined as follows:

1. For P-T cases 1 and 2 (see Issue 3) at 170 psig, the conditional probability of reactor building leak levels for WWRaW or WWRbW.

2. For P-T cases 1 and 2 at 170 psig, the conditional probability of reactor building leak levels for CWWR.

3. For P-T cases 3a at 150 psig and 800°F, the conditional probability of reactor building leak levels for WWRaW or WWRbW.

4. For P-T cases 3a at 150 psig and 800°F, the conditional probability of reactor building leak levels for CWWR.

5. For P-T cases 3b at 1200°F, the conditional probability of reactor building leak levels for WWRaW or WWRbW.

6. For P-T cases 3b at 1200°F, the conditional probability of reactor building leak levels for CWWR.

7. For P-T case 4 at 150 psig and 800°F, the conditional probability of reactor building leak levels for CWWR (others are level a).

Some judgment was required to convert Expert C's results into the same form as those of Experts A and B. There is no bypass up to .25 psig when the blowout panels on the refueling floor open. Then at 2 psig, floor slabs etc. start to go. At 3 psig structural failure may begin. From MELCOR runs for Peach Bottom, the pressure from WWR is in the range of 3 psig so we take the results from cases 1, 3, and 5 to be at 3 psig. The CWWR is in the 10 psig range so we take the results of cases 2, 4, and 6 to be at 10 psig. Interpolate linearly between points and extend on upper side by letting Level "b" go to zero at 15 psig, Level "c" increase until 15 psig then go to zero at 50 psig, and Level "d" increase to 1.0 at 50 psig. Table 4-3 is then converted to Table 4-4 for Expert C.

Table 4-4
Probability of Reactor Building Bypass for WWR--Expert C

Bypass Level	Pressure (psig) 0	.25	2	3	5	6	10	15	20	50
a	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
b	0.0	1.0	1.0	0.75	0.62	0.56	0.30	0.0	0.0	0.0
c	0.0	0.0	0.0	0.25	0.293	0.314	0.40	0.525	0.450	0.0
d	0.0	0.0	0.0	0.0	0.086	0.129	0.30	0.475	0.550	1.0

Table 4-5 provides the aggregate results formed by averaging the probabilities of the three experts.

Table 4-5
Probability of Reactor Building Bypass for WWR--Aggregate

Bypass Level	Pressure (kPa) 0	1.72	13.8	20.7	34.5	41.4	68.9	103.4	137.8	344.6
a	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
b	0.0	1.0	1.0	0.917	0.54	0.519	0.35	0.192	0.133	0.0
c	0.0	0.0	0.0	0.083	0.431	0.438	0.467	0.341	0.150	0.0
d	0.0	0.0	0.0	0.0	0.029	0.043	0.183	0.467	0.717	1.0

Individual Elicitations for Issue 4

Expert A's Elicitation

Effect of Wetwell Rupture on ECCS Survivability and Reactor Building Integrity at Peach Bottom

Description of Expert A's Rationale/Methodology

Rationale for Position on ECCS Survivability

Expert A felt that the probability of a catastrophic rupture was extremely small. He felt that a catastrophic rupture would definitely produce fragments and that a noncatastrophic rupture would produce a pressure pulse. He felt that the likelihood of a fragment fully penetrating the reactor building wall was less than 1% so it is not included in the Expert's assessment.

1. The Expert felt that the most likely direction of the fragments is radially outward from the containment centerline. The ceiling of the torus room is therefore an unlikely target.

2. The 2-ft-thick reinforced concrete ceilings are an effective barrier to missiles (fragments). Even if directed upwards, the fragments would not fully penetrate the torus room ceiling.

3. The CRD and condensate piping, which are located above the torus room, will never be in jeopardy from the fragments produced in a catastrophic wetwell rupture.

4. The HPSW lines are located along one side of the torus room and are not protected by the concrete wall. The Expert stated that there are eight segments of the wetwell in which the wetwell is equally likely to fail. The chance that the wetwell will fail in the area of the HPSW lines is therefore about 4/8 (0.50).

Method for Assessing Probability of Reactor Building Bypass

Expert A provided the probabilities of reactor building bypass conditional on pressure pulses in the reactor building. He left the calculation of the pressure pulses given wetwell rupture for the NUREG-1150 staff. The probabilities of the reactor building bypass levels discussed in the Issue Description are given in Table A-1 for several equivalent static pressures.

Table A-1
Descriptions of Equivalent Static Pressures

Equivalent Static Pressure (psig)	Reactor Building Bypass Level	Comments
P_{rb}* < 0.25	Level a	Reactor building blowout panels open at 0.25 psig
P_{rb} < 3.0	Level a and Level b	Same comment
P_{rb} < 5.0	Level b and Level b'	Concrete plugs and hatches in corner room open
P_{rb} < 10.0	Level b'	Some leakage to environment; some to reactor building blowout panels
P_{rb} < 20.0	Level b' and Level d	Some chance of reactor building structural failure
P_{rb} > 20.0	Level d	Virtually certain of structural failure

*P_{rb}: equivalent static pressure (psig) in the reactor building.

Level b': a new level defined by the Expert. Concrete plugs in the torus room lift, leakage into the corner room, and hatches open there to the environment (about 150 ft^2) and to the reactor building (about 200 ft^2). For our analysis, this is equivalent to level c, a large bypass of the reactor building.

Results of Expert A's Elicitation

Probability of Injection Line Failure Due to Wetwell Rupture

1. The probability of failure of the CRD lines or the condensate lines given rupture in the wetwell is essentially zero (see preceding section).

2. The probability of failure of the HPS waterline, given a catastrophic rupture in the wetwell, is about 0.50. This represents 4/8 (see preceding section).

Probability of Reactor Building Bypass Due to Wetwell Rupture

The probabilities of Levels a, b, b', and d are shown as a function of pressure in Table A-2.

Table A-2
Probability of Reactor Building Bypass--Expert A

	Pressure (psig)						
	0	.25	3	5	10	15	20
Level a	1.0	0.0	0.0	0.0	0.0	0.0	0.0
Level b	0.0	1.0	1.0	0.0	0.0	0.0	0.0
Level b'=c	0.0	0.0	0.0	1.0	1.0	0.5	0.0
Level d	0.0	0.0	0.0	0.0	0.0	0.5	1.0

Expert A said to use linear interpolation for the transition from Level "b" to "b'" (between 3 and 5 psig) and for Level "b'" to "d" (between 10 and 20 psig). At .25 psig, Level a switches to Level "b" as the blowout panels open.

To read the table:

1. Below 0.25 psig--Level "a" occurs.

2. Between 0.25 and 3 psig--Level "b" occurs.

3. Between 3 and 5 psig--a linear transfer from Level "b" to Level "b'" occurs.

4. Between 5 and 10 psig--Level "b'" occurs.

5. Between 10 and 20 psig--a linear transfer from Level "b'" to Level "d" occurs.

6. Above 20 psig--Level "d" occurs.

For example, at 15 psig there is a 50% probability that the reactor building bypass level is Level "b'" and a 50% probability that the reactor building bypass level is Level "d".

Sources of Uncertainty

Fragments could impact the concrete torus room ceiling and could decrease the pressure capacity of the ceiling. The impact on side walls is inconsequential because they are below grade. The likelihood of fragments directed vertically is small; this was not accounted for in the Expert's elicitation.

Correlations with Other Variables

No correlations were specified by the expert for this issue.

Suggestions for Reducing Uncertainty

Additional information on the reactor building structure would help in reducing the uncertainty in the building response. No explicit calculations of reactor building structural capacity were made; capacity was estimated based on design pressure and assessed safety margin.

Expert B's Elicitation

Effect of Wetwell Rupture on ECCS Survivability and Reactor Building Integrity at Peach Bottom

Description of Expert B's Rationale/Methodology

In analyzing this issue, Expert B reasoned as follows:

1. The expected pressure at which the torus may rupture was 130 to 150 psig or above.

2. Two time regimes were important-before core damage and vessel breach. The Expert said that the response of the torus will be the same in these two cases since the temperature will be roughly the same.

3. The piping that is of interest is:

   (i) HPSW to RHR discharge lines, covers one half of torus room.

   (ii) Condensate piping in steam tunnel.

   (iii) CRD lines, penetrate DW at 78°, 112°, 248°, and 292°.

4. Existing hatches in the torus room roof slab vent either into the reactor building or directly to the outside.

5. Peach Bottom containment P-T failure analysis (see Peach Bottom P-T issue writeup) shows that the torus shell is thinner in the upper segment and that it will be near or at yield in the circumferential direction when rupture is expected to occur. A crack is therefore more likely to propagate.

6. Any of the eight non- [illegible] gments may rupture.

7. With the crack propagating from the stiffener location, along the circumference, the thinner upper torus segment can fragment into several pieces (worst case).

8. From physical considerations, weld detail etc., four to six fragments are expected. The weight of each fragment will be about 3000 to 4000 lbs.

9. Estimated velocity of impact will be about 150 ft/s.

10. The kinetic energy of the missiles is smaller than the tornado generated automobile missile.

11. The available concrete thickness (23 to 33 in.) will be adequate to withstand the missile at elev 135'-0".

12. The presence of steel beams on the bottom surface of the slab will deform the missile, thus dissipating energy.

13. Missiles are therefore not expected to be able to reach the CRD and condensate pipe locations.

14. HPWS/RHR line runs through the torus room and will be impacted if the break occurs in four of the eight non-vent segments.

15. The above calculations are based on decoupling pressure effects.

16. Because the torus area vents to the 135'-0" floor of the reactor building (about 500 ft^2), the reactor building will pressurize as the torus depressurizes. However, the increase in reactor building pressure is not very well known.

17. Because of the vent to the outside (about 300 ft^2), part of the flow will bypass the reactor building.

Results of Expert B's Elicitation

Expert B decomposed the problem in the following way.

Rupture locations are the non-vent segments of the torus, of which there are eight. Failure of any of the segments is equally likely. Independent of location, the likelihood of fragments is four times that of no fragments. The probability of fragments is .8, the probability of no fragments is .2. Even with fragments, all failures are ruled out except for impact and failure of the HPSW/RHR lines. The probability of impact is non-zero only for four of the non-vent segments near the piping. Given impact, the probability of failure is 1.0. If there are no fragments, then failure of the piping is negligible and the reactor building failure is dependent on peak pressure and venting considerations.

Because of the lack of structural information on the reactor building, all of the experts based their failure pressure distribution on their general knowledge of similar structures. The Expert said that the building was designed to roughly 3 psig and should be able to withstand up to 6 psig. The probability of failure was therefore:

Pressure (psig)	Probability of Failure
0	0
6	0
10	.25
20	>.5
50	1.0

The implication of Expert B's elicitation was that this would be a gross failure of the reactor building and, that, this failure would result in what we would classify as a Level "d" bypass. The Expert did not consider the blowout panels. Since no significant leak is possible below .25 psig when the blowout panels rupture, we can construct the following table for leakage level vs pressure:

	Pressure					
	0	.25	6	10	20	50
Level a	1.0	1.0	0	0	0	0
Level b	0	1.0	1.0	.75	.40	0
Level c	0	0	0	0	0	0
Level d	0	0	0	.25	.60	1.0

Where we have used .6 to represent the Expert's assessment of >.5 and used our general knowledge of the reactor building to fill in the lower portion of the curve (i.e., < " psig).

Sources of Uncertainty

The Expert identified the following areas of uncertainty:

1. Will the torus rupture be a large leakage or fragmentation of the torus shell?

2. What will be the weight and velocity of the fragments?

3. What will be the pressure in the torus after the blowdown?

4. What will be the pressure in the reactor building?

Correlation with Other Variables

The Expert did not specify any correlation with other variables.

Suggested Methods of Reducing Uncertainty

The Expert said that if more information could be obtained on the structural strength of the reactor building, then the failure pressure could be specified more precisely.

Expert C's Elicitation

Effect of Wetwell Rupture on ECCS Survivability and Reactor Building Integrity at Peach Bottom

Determination of Expert C's Rationale/Methodology

The Expert tied his elicitation on this issue to his elicitation on the P-T induced containment failure. He used the same cases as before and the same failure modes and probabilities. For the catastrophic wetwell rupture case, he then branched out to the cases for this issue.

Results of Expert C's Elicitation

For P-T Cases 1, 2, and 3 at 170 psig and < 500°F, the conditional probability of failing due to CWWR:

1. The reactor building only = .18
2. The HPSW pipe only = .04
3. Both reactor building and HPSW pipe = .08
4. Failing neither = .70

For P-T Cases 1, 2, and 3 at 150 psig and < 500°F, the conditional probability of failing due to CWWR:

1. The reactor building only = .39
2. The HPSW pipe only = .03
3. Both reactor building and HPSW pipe = .09
4. Failing neither = .55

For P-T Case 3a at 150 psig and 800°F, the conditional probability of failing due to CWWR:

1. The reactor building only = .08
2. The HPSW pipe only = .06
3. Both reactor building and HPSW pipe = .06
4. Failing neither = .80

For P-T Cases 1 and 2 at 170 psig, the conditional probability of reactor building leak levels for WWRaW or WWRbW is:

1. Level a = .70
2. Level b = .05
3. Level c = .25
4. Level d = .00

For P-T Cases 1 and 2 at 170 psig, the conditional probability of reactor building leak levels for CWWR is:

1. Level a = .20
2. Level b = .10
3. Level c = .40
4. Level d = .30

For P-T Cases 3a at 150 psig and 600°F, the conditional probability of reactor building leak levels for WWRaW or WWRbW is:

1. Level a = .80
2. Level b = .05
3. Level c = .15
4. Level d = .00

For P-T Cases 3a at 150 psig and 800°F, the conditional probability of reactor building leak levels for CWWR is:

1. Level a = .30
2. Level b = .10
3. Level c = .40
4. Level d = .20

For P-T Cases 3b at 1200°F, the conditional probability of reactor building leak levels for WWRaW or WWRbW is:

1. Level a = .70
2. Level b = .05
3. Level c = .25
4. Level d = 0.0

For P-T Case 3b at 1200°F, the conditional probability of reactor building leak levels for CWWR is:

1. Level a = .20

2. Level b = .10

3. Level c = .40

4. Level d = .30

For P-T Case 4 at 150 psig and 800°F, the conditional probability of reactor building leak levels for CWWR (others are Level "a") is:

1. Level a = .08

2. Level b = .06

3. Level c = .06

4. Level d = 0.80

Because of the blowout panels to the outside on the refueling floor and to the turbine building, there will always be some bypass for WWR. Therefore, the Expert's Level "a" is really Level "b" for the purposes of our modeling of this issue and the two results for "a" and "b" will be added together in the aggregation.

Sources of Uncertainty

Expert C suggested that more information on the structural strength of the reactor building would enable him to reduce the uncertainty on the reactor building failure pressure for the different scenarios.

Correlations with Other Variables

No correlations were specified by the expert for this issue.

Suggested Methods for Reducing Uncertainty

Obtain more information on the reactor building structure.

5.5 Issue 5: Containment Failure at Sequoyah Due to Static Pressure

Experts consulted: David Clauss, Sandia National Laboratories; Kam Mohktarian, Chicago Bridge & Iron; Don Wesley, IMPELL.

Issue Description

The issue is: what distribution characterizes the failure pressures for static loading of the Sequoyah Containment? what conditional probabilities describe the failure modes for each pressure?

The Sequoyah ice condenser containment is in the shape of a cylinder with a hemispherical dome. There is an outer building constructed of reinforced concrete, but this issue concerns only with the pressure boundary. The pressure boundary is located within the concrete shed structure and is a free-standing steel shell with external stiffeners. The foundation is a reinforced concrete slab, and the steel shell is embedded in this slab. The design pressure is 10.8 psig. The free volume is about 1,200,000 ft^3. The containment consists of three compartments: the lower compartment which contains the RCS, steam generators, etc.; the ice condenser itself; and the upper compartment, which contains the polar crane and little else.

Three pressure rise cases were described in the original definition of the issue:

1. Rapid pressure increase at vessel breach;
2. Late deflagration; and
3. Late, gradual pressure rise.

Typical rise times for cases 1 and 2 would be on the order of a few seconds. While very high atmospheric temperatures might be observed for a fraction of a minute in case 1, the bulk temperature of the steel liner which forms the pressure boundary is not expected to exceed 300 to 350°F for any of the cases. Containment failure due to detonations is considered in another issue.

It is necessary to distinguish between failure locations that would bypass the ice condenser and those which would not. Failure of the dome, or of the equipment hatch, creates a path from the upper compartment to the environment, which does not bypass the ice condenser. Failure in the ice condenser itself is assumed to create a bypass, but 60° of the containment wall is not occupied by the ice condenser, and failure in this segment would not bypass the ice condenser. Failure at the cylinder-basemat junction is below the bottom of the ice condenser, and opens a path from the lower compartment to the outside, bypassing the ice condenser completely. The concrete building surrounding the steel shell is not considered to be a significant barrier as its pressure capability is less than that of the steel shell.

The original issue definition of a large hole or rupture was an opening larger than 1.0 ft^2, which resulted in depressurization in less than about 2 h. A small hole or leak was anything smaller than 1.0 ft^2, which did not result in depressurization in less than about 2 h. A review of this matter showed that large dry containments would depressurize in 2 h for holes sizes on the order of 0.3 to 0.5 ft^2. Thus a small hole or leak should have been on the order of 0.1 ft^2, and 1.0 ft^2 is definitely a large hole or rupture.

The failure mode "Catastrophic Rupture" (CR) was added at the time of elicitation. The containment failure implied by this failure mode is complete failure of a substantial portion of the containment pressure boundary, with possible disruption of the piping systems that penetrate or are attached to the containment wall. Catastrophic rupture is judged to always result in bypass of the ice condenser. No gross structural failure is implied by the "Rupture" failure mode.

Summary of Results

The three panel members considering this issue all agreed that the three cases could be treated together since the pressure rise times were slow enough that structural response could be considered static. However, they stressed that the pressure rise time and the ultimate load in the absence of failure must be considered in determining the failure mode since the development of a leak will not arrest the pressure rise for events with fast rise times such as deflagrations and direct containment heating. Two of the three concluded that high temperature conditions (500 to 600°F) warranted separate consideration. One expert identified a separate failure mode for the higher temperature range. However, there was confusion in the initial issue statement as to the exact meaning of the temperatures given there. The temperatures in the 500 to 600°F range are transitory air temperatures in the upper compartment, not bulk temperatures of the structural steel shell. The surface temperatures of the shell may reach these temperatures briefly, but the average temperature in the membrane never exceeds 300 to 350°F. Thus the high temperature results were not needed, and were not utilized.

The distributions of the three experts, in the form received, are given in Table 5-1 for Expert A, Table 5-2 for Expert B, and Table 5-3 for Expert C. These tables were transformed into a common form for aggregating. These are Tables 5-4, 5-5, and 5-6. The data manipulations required are discussed in the next section. Note that the conditional probabilities for failure mode are interval probabilities, that is, they apply only for failure in the interval between the pressure indicated and the pressure on the previous line.

Expert A concluded that the containment would fail by either catastrophic rupture of the cylindrical shell or buckling of the equipment hatch. He provided independent cumulative failure probabilities for each location as shown in Table 5-1. Failure of the shell would always be a catastrophic rupture, which bypasses the ice condenser. Buckling of the equipment hatch would always be a leak. Because of the location of the hatch, this leak does not bypass the ice condenser. Expert A thought that the median pressure for failure of the shell was 80 psig, whereas hatch buckling would only reach a cumulative probability of 10% at 120 psig. Thus, Expert A's conclusions were heavily weighted toward catastrophic rupture.

Table 5-1
Sequoyah Static. Failure Probabilities for Expert A

	Cylinder Shell		Hatch Buckling	
Pressure (psig)	Cumulative Failure Prob.	Conditional Prob. Catastrophic Rup.	Cumulative Failure Prob.	Conditional Prob. Leak
20	0.000	1.000	0.000	1.000
25	0.000	1.000	0.000	1.000
30	0.000	1.000	0.000	1.000
35	0.000	1.000	0.000	1.000
40	0.000	1.000	0.000	1.000
45	0.000	1.000	0.000	1.000
50	0.001	1.000	0.000	1.000
55	0.010	1.000	0.000	1.000
60	0.035	1.000	0.000	1.000
65	0.100	1.000	0.000	1.000
70	0.210	1.000	0.000	1.000
75	0.340	1.000	0.000	1.000
80	0.500	1.000	0.001	1.000
85	0.630	1.000	0.010	1.000
90	0.760	1.000	0.020	1.000
95	0.840	1.000	0.033	1.000
100	0.920	1.000	0.047	1.000
105	0.960	1.000	0.060	1.000
110	0.980	1.000	0.073	1.000
115	0.990	1.000	0.087	1.000
120	1.000	1.000	0.100	1.000

Expert B thought that the containment could fail by rupture of the cylindrical shell, ovalization of the hatch flange, or failure of the anchorage system (see Table 5-2). He provided independent distributions for each location. For each location, he provided conditional probabilities for failure mode. For rupture of the shell, his median failure pressure was 60 psig. For shell failure, he was certain that the mode would be rupture below 50 psig and catastrophic failure above 55 psig. It was assumed that the shell ruptures would be randomly distributed in azimuth. As the ice

Table 5-2
Sequoyah Static. Failure Probabilities for Expert B

	Cylinder Shell			Hatch Ovalization			Anchorage Failure		
Pressure (psig)	Cumul. Failure Prob.	Cond. Prob. Rupture	Cond. Prob. Cat. Rup.	Cumul. Failure Prob.	Cond. Prob. Leak	Cond. Prob. Rupture	Cumul. Failure Prob.	Cond. Prob. Leak	Cond. Prob. Rupture
20	0.000	1.000	0.000	0.000	1.000	0.000	0.000	1.000	0.000
25	0.000	1.000	0.000	0.000	1.000	0.000	0.000	1.000	0.000
30	0.000	1.000	0.000	0.000	1.000	0.000	0.000	1.000	0.000
35	0.005	1.000	0.000	0.000	1.000	0.000	0.000	1.000	0.000
40	0.006	1.000	0.000	0.000	1.000	0.000	0.000	1.000	0.000
45	0.008	1.000	0.000	0.000	1.000	0.000	0.000	1.000	0.000
50	0.010	0.800	0.200	0.000	1.000	0.000	0.000	1.000	0.000
55	0.100	0.300	0.700	0.000	1.000	0.000	0.000	1.000	0.000
60	0.500	0.000	1.000	0.000	1.000	0.000	0.000	1.000	0.000
65	0.620	0.000	1.000	0.010	1.000	0.000	0.100	1.000	0.000
70	0.750	0.000	1.000	0.990	0.800	0.200	0.250	1.000	0.000
75	0.900	0.000	1.000	0.999	0.200	0.800	0.500	0.700	0.300
80	0.990	0.000	1.000	0.999	0.000	1.000	0.600	[illegible]	0.700
85	0.992	0.000	1.000	0.999	0.000	1.000	0.850	0.000	1.000
90	0.994	0.000	1.000	0.999	0.000	1.000	0.900	0.000	1.000
95	0.995	0.000	1.000	1.000	0.000	1.000	0.930	0.000	1.000
100	0.996	0.000	1.000	1.000	0.000	1.000	0.960	0.000	1.000
105	0.997	0.000	1.000	1.000	0.000	1.000	0.990	0.000	1.000
110	0.998	0.000	1.000	1.000	0.000	1.000	0.995	0.000	1.000
115	0.999	0.000	1.000	1.000	0.000	1.000	0.999	0.000	1.000
120	1.000	0.000	1.000	1.000	0.000	1.000	1.000	0.000	1.000

condenser occupies 300° of the outer wall of the containment, five sixths of the shell ruptures will occur in the ice condenser and will therefore bypass it, while one sixth of the shell ruptures will not bypass the ice condenser. Expert B was certain that ovalization of the hatch flange would cause containment failure between 65 and 70 psig. As the size of the opening depends directly upon the expansion of the shell, which in turn causes the ovalization of the flange, he was certain it would be a leak below 70 psig and a rupture above 75 psig. For anchorage failure, Expert B's median failure pressure was 75 psig. He was certain that the mode would be leak below 75 psig and catastrophic failure above 80 psig. All anchorage failures will bypass the ice condenser.

Expert C provided joint cumulative failure probabilities for the five failure modes directly, as shown in Table 5-3. His median failure pressure is about 54 psig. At the lower failure pressures all failure modes are possible, but at the higher failure pressures the predominant failure mode is CR.

Table 5-3
Sequoyah Static. Failure Probabilities for Expert C

	Joint Cumulative Probabilities					
Pressure (psig)	Leak No Bypass	Leak Bypass	Rupture No Bypass	Rupture Bypass	Catastrophic Rupture	All Modes
20	0.000	0.000	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000	0.000	0.000
30	0.015	0.025	0.005	0.010	0.000	0.055
35	0.030	0.050	0.010	0.020	0.000	0.110
40	0.035	0.055	0.020	0.060	0.005	0.175
45	0.040	0.060	0.030	0.100	0.010	0.240
50	0.040	0.065	0.100	0.130	0.025	0.360
55	0.040	0.070	0.170	0.160	0.040	0.480
60	0.040	0.070	0.190	0.180	0.170	0.650
65	0.040	0.070	0.210	0.200	0.300	0.820
70	0.040	0.070	0.215	0.205	0.380	0.910
75	0.040	0.070	0.220	0.210	0.460	1.000
80	0.040	0.070	0.220	0.210	0.460	1.000
85	0.040	0.070	0.220	0.210	0.460	1.000
90	0.040	0.070	0.220	0.210	0.460	1.000
95	0.040	0.070	0.220	0.210	0.460	1.000
100	0.040	0.070	0.220	0.210	0.460	1.000
105	0.040	0.070	0.220	0.210	0.460	1.000
110	0.040	0.070	0.220	0.210	0.460	1.000
115	0.040	0.070	0.220	0.210	0.460	1.000
120	0.040	0.070	0.220	0.210	0.460	1.000

Table 5-4
Conversion of Expert A's Elicitation Values from Table 5-1

Pressure (psig)	Cumulative Failure Probability	Failure Prob. Density	Interval Conditional Probabilities: Leak No Bypass	Leak Bypass	Rupture No Bypass	Rupture Bypass	Catastrophic Rupture
20	0.000	0.000	0.000	0.000	0.000	0.000	1.000
25	0.000	0.000	0.000	0.000	0.000	0.000	1.000
30	0.000	0.000	0.000	0.000	0.000	0.000	1.000
35	0.000	0.000	0.000	0.000	0.000	0.000	1.000
40	0.000	0.000	0.000	0.000	0.000	0.000	1.000
45	0.000	0.000	0.000	0.000	0.000	0.000	1.000
50	0.001	0.001	0.000	0.000	0.000	0.000	1.000
55	0.010	0.009	0.000	0.000	0.000	0.000	1.000
60	0.035	0.025	0.000	0.000	0.000	0.000	1.000
65	0.100	0.065	0.000	0.000	0.000	0.000	1.000
70	0.210	0.110	0.000	0.000	0.000	0.000	1.000
75	0.340	0.130	0.000	0.000	0.000	0.000	1.000
80	0.501	0.160	0.004	0.000	0.000	0.000	0.996
85	0.634	0.133	0.029	0.000	0.000	0.000	0.971
90	0.765	0.131	0.023	0.000	0.000	0.000	0.977
95	0.845	0.080	0.032	0.000	0.000	0.000	0.968
100	0.924	0.078	0.021	0.000	0.000	0.000	0.979
105	0.962	0.039	0.020	0.000	0.000	0.000	0.980
110	0.981	0.019	0.021	0.000	0.000	0.000	0.979
115	0.991	0.009	0.022	0.000	0.000	0.000	0.978
120	1.000	0.009	0.022	0.000	0.000	0.000	0.978

Table 5-5
Conversion of Expert B's Elicitation Values from Table 5-2

Pressure (psig)	Cumulative Failure Probability	Failure Prob. Density	Interval Conditional Probabilities: Leak No Bypass	Leak Bypass	Rupture No Bypass	Rupture Bypass	Catastrophic Rupture
20	0.000	0.000	0.000	0.000	0.167	0.833	0.000
25	0.000	0.000	0.000	0.000	0.167	0.833	0.000
30	0.000	0.000	0.000	0.000	0.167	0.833	0.000
35	0.005	0.005	0.000	0.000	0.167	0.833	0.000
40	0.006	0.001	0.000	0.000	0.167	0.833	0.000
45	0.008	0.002	0.000	0.000	0.167	0.833	0.000
50	0.010	0.002	0.000	0.000	0.133	0.667	0.200
55	0.100	0.090	0.000	0.000	0.050	0.250	0.700
60	0.500	0.400	0.000	0.000	0.000	0.000	1.000
65	0.661	0.161	0.043	0.435	0.000	0.000	0.522
70	0.998	0.337	0.622	0.119	0.156	0.000	0.103
75	1.000	0.002	0.004	0.428	0.018	0.183	0.367
80	1.000	0.000	0.000	0.231	0.000	0.538	0.231
85	1.000	0.000	0.000	0.000	0.002	0.960	0.038
90	1.000	0.000	0.000	0.000	0.002	0.960	0.038
95	1.000	0.000	0.000	0.000	0.000	0.000	1.000
100	1.000	0.000	0.000	0.000	0.000	0.000	1.000
105	1.000	0.000	0.000	0.000	0.000	0.000	1.000
110	1.000	0.000	0.000	0.000	0.000	0.000	1.000
115	1.000	0.000	0.000	0.000	0.000	0.000	1.000
120	1.000	0.000	0.000	0.000	0.000	0.000	1.000

Table 5-6
Conversion of Expert C's Elicitation Values from Table 5-3

Pressure (psig)	Cumulative Failure Probability	Failure Prob. Density	Interval Conditional Probabilities: Leak No Bypass	Leak Bypass	Rupture No Bypass	Rupture Bypass	Catastrophic Rupture
20	0.000	0.000	0.273	0.455	0.091	0.182	0.000
25	0.000	0.000	0.273	0.455	0.091	0.182	0.000
30	0.055	0.055	0.273	0.455	0.091	.182	0.000
35	0.110	0.055	0.273	0.455	0.091	0.182	0.000
40	0.175	0.065	0.077	0.077	0.154	0.615	0.077
45	0.240	0.065	0.077	0.077	0.154	0.615	0.[illegible]
50	0.360	0.120	0.000	0.042	0.583	0.250	0.12[illegible]
55	0.480	0.120	0.000	0.042	0.583	0.250	0.125
60	0.650	0.170	0.000	0.000	0.118	0.118	0.765
65	0.820	0.170	0.000	0.000	0.118	0.118	0.765
70	0.910	0.090	0.000	0.000	0.056	0.056	0.889
75	1.000	0.090	0.000	0.000	0.056	0.056	0.889
80	1.000	0.000	0.000	0.000	0.056	0.056	0.889
85	1.000	0.000	0.000	0.000	0.056	0.056	0.889
90	1.000	0.000	0.000	0.000	0.056	0.056	0.889
95	1.000	0.000	0.000	0.000	0.056	0.056	0.889
100	1.000	0.000	0.000	0.000	0.056	0.056	0.889
105	1.000	0.000	0.000	0.000	0.056	0.056	0.889
110	1.000	0.000	0.000	0.000	0.056	0.056	0.889
115	1.000	0.000	0.000	0.000	0.056	0.056	0.889
120	1.000	0.000	0.000	0.000	0.056	0.056	0.889

Table 5-7 gives the aggregate distribution. The three individual distributions were aggregated as explained in the next section. The median of the average distribution is about 64 psig. The 5 and 95% failure pressures are about 39 and 95 psig, respectively. At the very lowest failure pressures, leak is the dominant failure mode. Above the median failure pressure, catastrophic rupture is the dominant failure mode.

Figure 5-1 shows the cumulative failure probability for static failure pressure at Sequoyah for the three experts who considered this issue and the aggregate. Figures 5-2 through 5-6 are plots of the conditional probabilities for the five failure modes. These plots do not have a smooth monotonic appearance since each expert thought that each failure mode was most likely to occur in a different pressure range.

Table 5-7
Aggregate Static Failure Probabilities for Sequoyah

			Interval Conditional Probabilities				
Pressure (psig)	Cumulative Failure Probability	Failure Prob. Density	Leak No Bypass	Leak Bypass	Rupture No Bypass	Rupture Bypass	Catastrophic Rupture
20	0.000	0.000	0.273	0.455	0.091	0.182	0.000
25	0.000	0.000	0.273	0.455	0.091	0.182	0.000
30	0.018	0.018	0.273	0.455	0.091	0.182	0.000
35	0.038	0.020	0.250	0.417	0.097	0.236	0.000
40	0.060	0.022	0.076	0.076	0.154	0.619	0.076
45	0.083	0.022	0.075	0.075	0.154	0.622	0.075
50	0.124	0.041	0.000	0.041	0.571	0.255	0.133
55	0.197	0.073	0.000	0.023	0.340	0.240	0.397
60	0.395	0.198	0.000	0.000	0.034	0.034	0.933
65	0.527	0.132	0.018	0.177	0.050	0.050	0.704
70	0.706	0.179	0.390	0.075	0.107	0.009	0.419
75	0.780	0.074	0.000	0.004	0.023	0.024	0.950
80	0.833	0.054	0.004	0.000	0.000	0.000	0.996
85	0.878	0.044	0.029	0.000	0.000	0.000	0.971
90	0.922	0.044	0.023	0.000	0.000	0.000	0.977
95	0.948	0.027	0.032	0.000	0.000	0.000	0.968
100	0.975	0.026	0.021	0.000	0.000	0.000	0.979
105	0.987	0.013	0.020	0.000	0.000	0.000	0.980
110	0.994	0.006	0.021	0.000	0.000	0.000	0.979
115	0.997	0.003	0.022	0.000	0.000	0.000	0.978
120	1.000	0.003	0.022	0.000	0.000	0.000	0.978

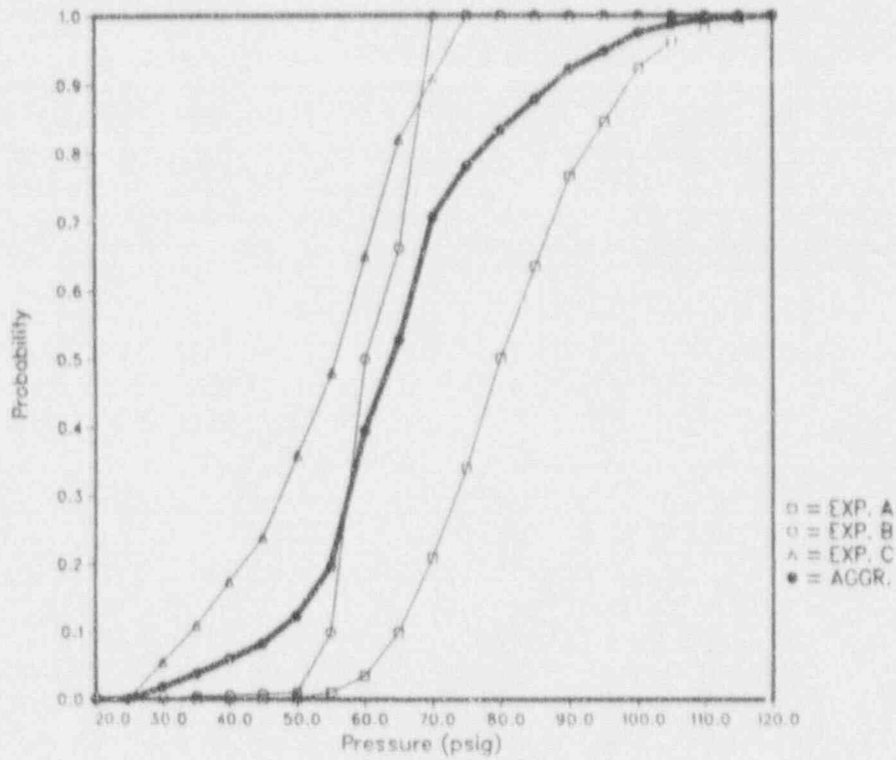

Figure 5-1. Cumulative Failure Probability.

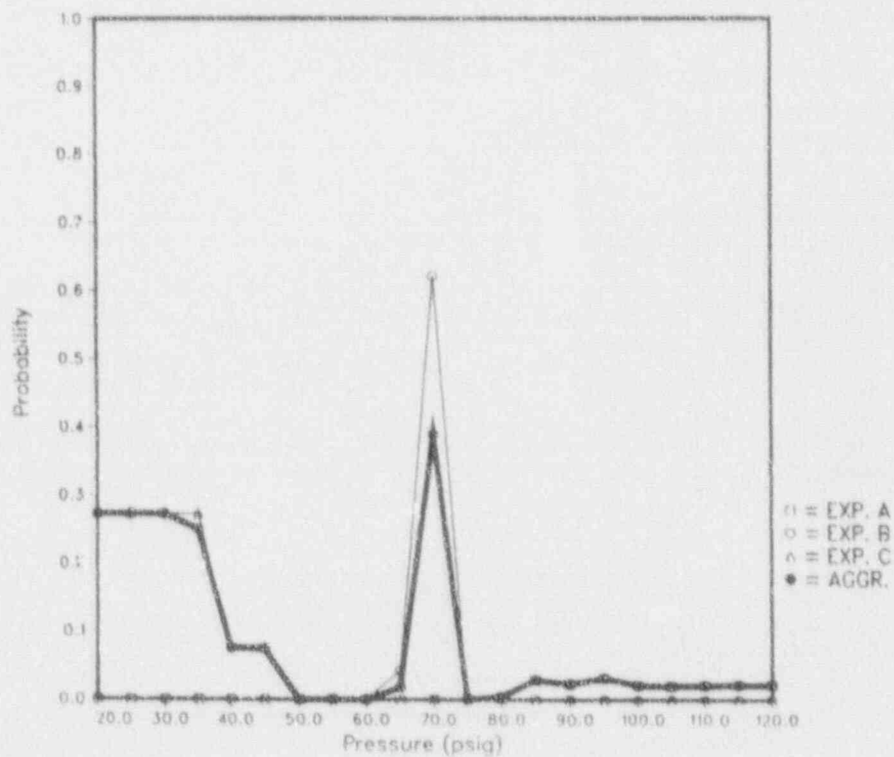

Figure 5-2. Conditional Probability for Failure Mode: Leak, No Bypass.

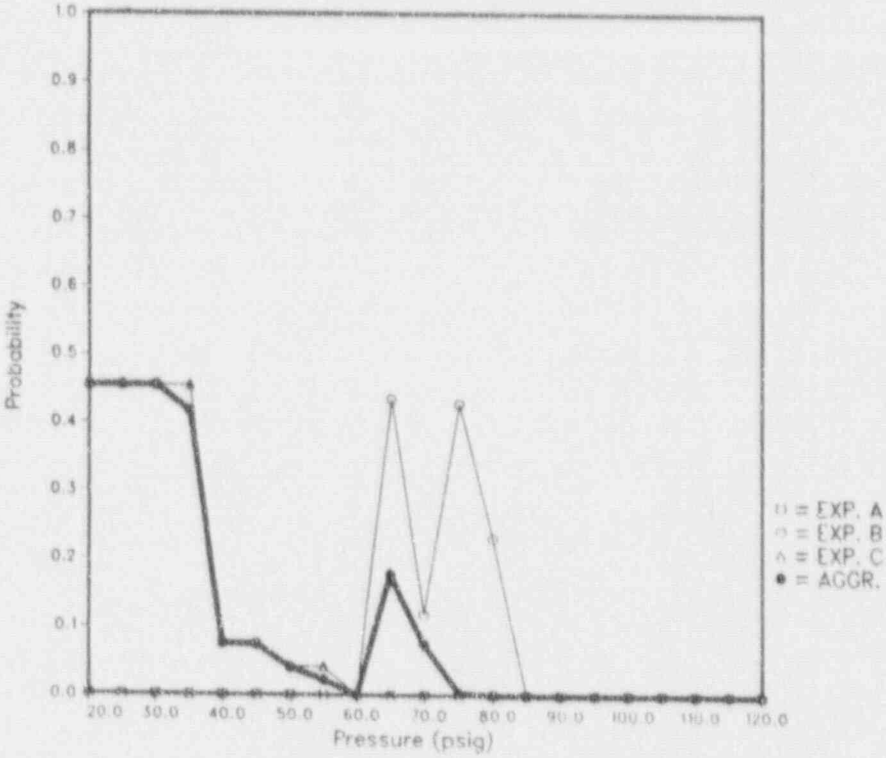

Figure 5-3. Conditional Probability for Failure Mode: Leak, Bypass.

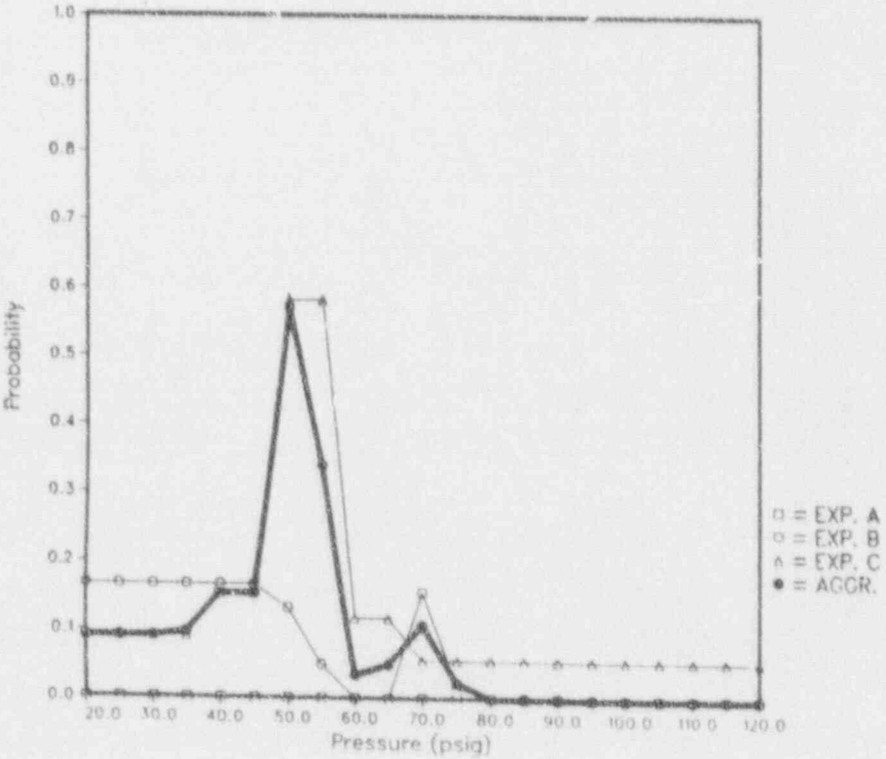

Figure 5-4. Conditional Probability for Failure Mode: Rupture, No Bypass.

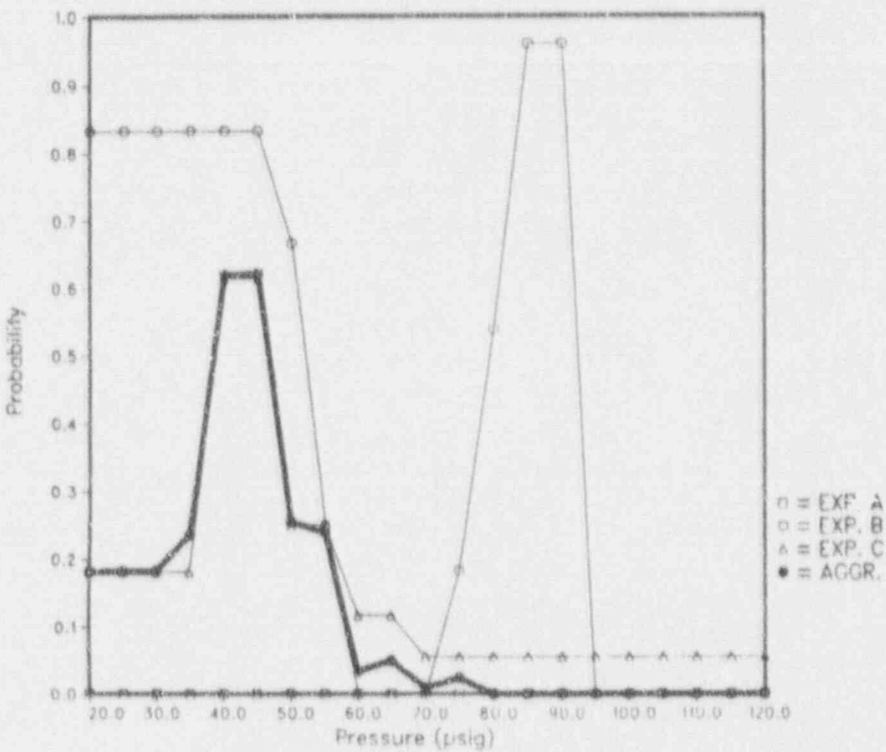

Figure 5-5. Conditional Probability for Failure Mode: Rupture with Bypass.

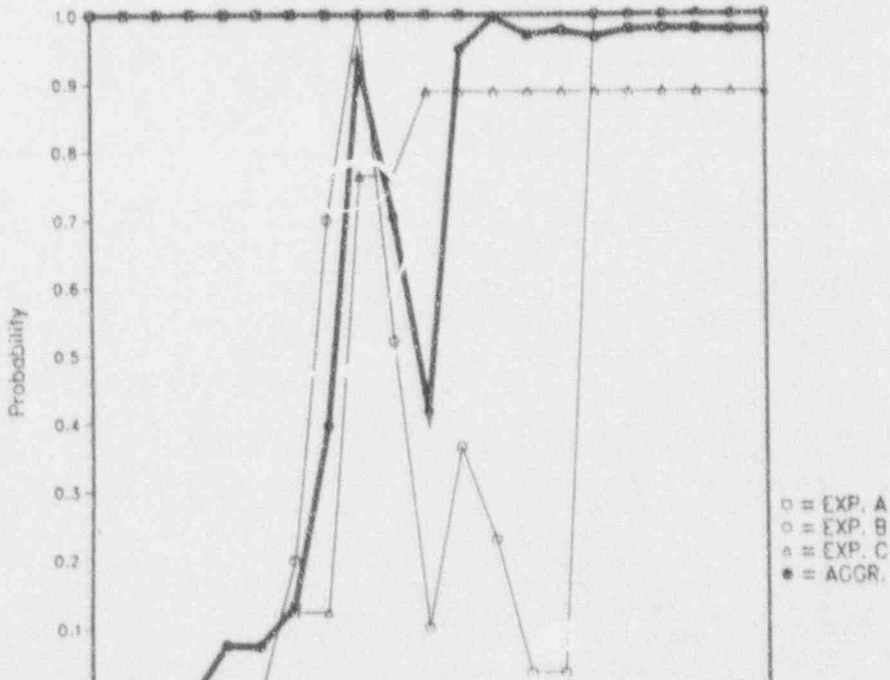

Figure 5-6. Conditional Probability for Failure Mode: Catastrophic Rupture.

Method of Aggregation

Some manipulation was required to get each expert's elicitation values into the form of Tables 5-1, 5-2, and 5-3, so they could be combined to obtain Table 5-7. The distributions the experts provided were not for 5 psig increments (the actual values provided are given below), so interpolation has been used to determine probabilities for the 5 psig increments.

Converting the results of Expert A from Table 5-1 to Table 5-4 was straightforward since he had only shell and hatch failures, and the shell failures are always catastrophic failure and the hatch failures are always leak--no bypass. The Cumulative Failure Probability column in Table 5-4 is formed by the equation:

$$CFP(i) = 1 - (1 - G_{sh}(i)) * (1 - G_{ha}(i))$$

for each pressure interval i, where:

CFP(i) is the total cumulative failure probability for interval i;

$G_{sh}(i)$ is the independent cumulative probability for failure of the cylindrical shell for interval i;

and

$G_{ha}(i)$ is the independent cumulative probability for failure of the hatch by buckling for interval i.

Above 75 psig, the standard formula for converting independent distributions to interval conditional probabilities was used. It is:

$$C_{ln}(i) = [(2 - CFP(i) - CFP(i-1)) * (G_{ha}(i) - G_{ha}(i-1))] / [(2 - G_{ha}(i) - G_{ha}(i-1)) * (CFP(i) - CFP(i-1))]$$

for each pressure interval i, where CFF(i), $G_{sh}(i)$, and $G_{ha}(i)$ have been defined above, and

$C_{ln}(i)$ is = the interval conditional probability for leak - no bypass for interval i.

The equation for the interval conditional probability for CR, $C_{cr}(i)$, is analogous. The standard formulas did not give meaningful results for 120 psig, so the interval conditional probabilities for the previous interval were used.

Converting the results of Expert B from Table 5-2 to Table 5-5 was much more complicated since Expert B provided independent distributions for each location, and, for each location, conditional probabilities for failure mode. The Cumulative Failure Probability columns in Tables 5-2 and 5-5 are easily formed from:

$$CFP(i) = 1 - (1 - G_{sh}(i)) * (1 - G_{ha}(i)) * (1 - G_{an}(i))$$

for each pressure interval i, where where CFP(i), $G_{sh}(i)$, and $G_{ha}(i)$ have been defined above, and

$G_{an}(i)$ is the independent cumulative probability for failure of the anchorage for interval i.

The interval conditional probabilities were more difficult to obtain. First the interval probability densities shown in Table 5-8 were obtained by backward differencing. Next the conditional probabilities in Table 5-2 were used to obtain the joint probability densities (joint on pressure interval, location, and mode) shown in Table 5-9. For rupture-no bypass failure of the shell, the shell failure probability density from Table 5-8 is multiplied by one sixth of the conditional probability for rupture for the shell (the third column) in Table 5-2 since only one sixth of the ruptures will not bypass the ice condenser. The other columns in Table 5-9 are found analogously.

The interval conditional probabilities shown in Table 5-5 are formed by considering similar failure modes together without regard to location and normalizing by the total density for that interval. There is only one catastrophic failure column (shell) in Table 5-9, so the entry in Table 5-5, for a given pressure interval, is just the entry in Table 5-9 divided by the sum of all the entries in that row in Table 5-9. There are two columns for rupture-bypass (shell and anchorage) in Table 5-9, so the entry in Table 5-5 is the sum of both of rupture-bypass entries in Table 5-9 divided by the sum of all the entries in that row in Table 5-9. Table 5-5 has the results of Expert B in the proper form for averaging with the results of Experts A and C.

Expert C gave joint cumulative probabilities for pressure and failure modes as shown in Table 5-3. The All Modes column, which is the sum of the five columns to the left of it, is therefore the cumulative failure probability shown in Table 5-6. The Failure Probability Density column in Table 5-2 is the backward difference of the cumulative failure probability. The Interval Conditional Probabilities in Table 5-6 are formed by considering the joint probability densities. That is, the backward differences of the entries in Table 5-3 are divided by the total Failure Probability Density, the second column in Table 5-6, to get the Interval Conditional Probabilities in Table 5-6.

Table 5-8
Interval Probabilty Densities

Pressure (psig)	Total Cumulative Failure Probability	Failure Probability Density		
		Shell	Hatch	Anchorage
20	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000
35	0.005	0.005	0.000	0.000
40	0.006	0.001	0.000	0.000
45	0.008	0.002	0.000	0.000
50	0.010	0.002	0.000	0.000
55	0.100	0.090	0.000	0.000
60	0.500	0.400	0.000	0.000
65	0.661	0.120	0.010	0.100
70	0.998	0.130	0.980	0.150
75	1.000	0.150	0.009	0.250
80	1.000	0.090	0.000	0.300
85	1.000	0.002	0.000	0.050
90	1.000	0.002	0.000	0.050
95	1.000	0.001	0.000	0.030
100	1.000	0.001	0.000	0.030
105	1.000	0.001	0.000	0.030
110	1.000	0.001	0.000	0.005
115	1.000	0.001	0.000	0.004
120	1.000	0.001	0.000	0.001

Table 5-9
Expert B's Joint Probability Densities

	Shell Joint Failure Probability Density			Hatch Joint Fail. Prob. Dens.		Anchor. Joint Fail.Prob.Dens.	
Pressure (psig)	Rupture No Bypass	Rupture Bypass	Catas. Rupture	Leak No Bypass	Rupture No Bypass	Leak Bypass	Rupture Bypass
20	0.000	0.000	0.000	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000	0.000	0.000	0.000
35	0.001	0.004	0.000	0.000	0.000	0.000	0.000
40	0.000	0.001	0.000	0.000	0.000	0.000	0.000
45	0.000	0.002	0.000	0.000	0.000	0.000	0.000
50	0.000	0.001	0.000	0.000	0.000	0.000	0.000
55	0.005	0.023	0.063	0.000	0.000	0.000	0.000
60	0.000	0.000	0.400	0.000	0.000	0.000	0.000
65	0.000	0.000	0.120	0.010	0.000	0.100	0.000
70	0.000	0.000	0.130	0.784	0.196	0.150	0.000
75	0.000	0.000	0.150	0.002	0.007	0.175	0.075
80	0.000	0.000	0.090	0.000	0.000	0.090	0.210
85	0.000	0.000	0.002	0.000	0.000	0.000	0.050
90	0.000	0.000	0.002	0.000	0.000	0.000	0.050
95	0.000	0.000	0.001	0.000	0.000	0.000	0.030
100	0.000	0.000	0.001	0.000	0.000	0.000	0.030
105	0.000	0.000	0.001	0.000	0.000	0.000	0.030
110	0.000	0.000	0.001	0.000	0.000	0.000	0.005
115	0.000	0.000	0.001	0.000	0.000	0.000	0.004
120	0.000	0.000	0.001	0.000	0.000	0.000	0.001

The aggregation of the cumulative failure probability is a straightforward averaging process. That is, the aggregate values of the cumulative failure probability for each pressure interval in Tables 5-4, 5-5, and 5-6 are summed and divided by three. For the interval conditional probabilities, the aggregate is formed by weighting each expert's interval conditional probability by the failure probability density for the interval. The equation used is:

$$C(i,m) = [\ C_A(i,m) * D_A(i) + C_B(i,m) * D_B(i) + C_C(i,m) * D_C(i)\ ]$$
$$/\ [\ D_A(i) + D_B(i) + D_C(i)\ ]$$

where:

$C(i,m)$ is the aggregate conditional probability for failure in mode m, given that the failure occurs in pressure interval i;

$C_j(i,m)$ is Expert j's conditional probability for failure in mode m, given that the failure occurs in pressure interval i; and

$D_j(i)$ is Expert j's probability that the containment will fail in pressure interval i.

This can be shown to be equivalent to averaging the joint probabilities. The proof is as follows: let

$D(i)$ be the aggregate probability that the containment will fail in pressure interval i;

$J_j(i,m)$ be Expert j's joint probability that the containment will fail in pressure interval i and in failure mode m; and

$J(i,m)$ be the aggregate joint probability that the containment will fail in pressure interval i and in failure mode m; and now

$$D(i) = [\ D_A(i) + D_B(i) + D_C(i)\ ] / 3$$

and

$$J(i,m) = [\ J_A(i,m) + J_B(i,m) + J_C(i,m)\ ] / 3.$$

The relationship between the failure probability density, D, the joint failure probability, J, and the conditional failure mode probability is:

$$J(i,m) = D(i) * C(i,m).$$

So

$$C(i,m) = J(i,m) / D(i) = (\ [\ J_A(i,m) + J_B(i,m) + J_C(i,m)\ ] / 3\ ) / (\ [\ D_A(i) + D_B(i) + D_C(i)\ ] / 3\ ).$$

Using the relationship between the density, the joint, and the conditional probabilities for each expert this becomes

$$C(i,m) = [\ C_A(i,m) * D_A(i) + C_B(i,m) * D_B(i) + C_C(i,m) * D_C(i)\ ] / [\ D_A(i) + D_B(i) + D_C(i)\ ]$$

as above.

Method of Determining Containment Failure

This section discusses the manner in which the results of the elicitations on this issue will be used in the event trees that follow the accident progression. For each observation in the sample, a sampling scheme selects a load pressure from a load distribution given by the Containment Loads Panel, and it selects a containment failure pressure from the aggregate curve given in Table 5-7. It also selects a random number between zero and one to be used to determine the mode of failure.

The load pressure and the containment failure pressure are compared by a user function in the event tree. If the load pressure is less than the containment failure pressure, the containment does not fail. If the load pressure is greater than or equal to the containment failure pressure, the containment fails. If the containment fails, the random number is used to determine the failure mode. Consider the following example: the failure pressure is 65 psig, the load pressure is [illegible] psig, and pressure rise is slow compared to the time it takes a leak to depressurize the containment. Because the occurrence of a leak will arrest the pressure rise, the interval conditional probability entries in Table 5-7 for 65 psig are used to determine the failure mode. The interval conditional probability for leak-no bypass is 0.018, so if the random number is less than 0.018, the failure mode is leak-no bypass. The interval conditional probability for leak-bypass is 0.177, so if the random number is between 0.018 and 0.195 (= 0.018 + 0.177) the failure mode is leak-bypass. The other failure modes are determined analogously. The following table gives the results for a failure pressure of 65 psig:

Range for Random Number	Failure Mode
0.000 - 0.018	Leak-no bypass
0.018 - 0.195	Leak-bypass
0.195 - 0.245	Rupture-no bypass
0.245 - 0.295	Rupture-bypass
0.295 - 1.000	Catastrophic Rupture

In Table 5-7, for 65 psig, the conditional probability for catastrophic failure is 0.704, not 0.705 as implied here. This difference is due to roundoff error.

If the pressure rise is fast compared to the time it takes a leak to depressurize the containment, the determination of the failure mode is more complicated. Again consider the example in which the failure pressure is 65 psig and the load pressure is 70 psig.

If a leak develops at 65 psig, the pressure will keep on rising, and a rupture or catastrophic failure may develop between 65 and 70 psig. To determine the appropriate failure probability density for determining the probabilities of ruptures and catastrophic failures between 65 and 70 psig, the portion of the distribution below 65 psig is discounted since failure has occurred at 65 psig. Thus, the density used to determine if an additional rupture may occur between 65 and 70 psig is not FPD(70) = 0.179, but FPD(70)/(1 - CFP(65)) = 0.179/0.473 = 0.378. The conditional probability of additional ruptures forming between 65 and 70 psig is the leak probability at 65 psig (0.018 + 0.177 = 0.195) times the appropriate failure density times the conditional rupture probability for the 70 psig interval. For the conditional probability of rupture-no bypass, the average of the values for 65 and 70 psig (0.5*(0.50 + 0.107) = 0.0785) is used. Thus, the conditional probability of rupture-no bypass for a fast pressure rise, failure pressure equal 65 psig, load pressure equal 70 psig is:

$$0.056 = 0.050 + 0.195 * 0.378 * 0.0785.$$

In general terms, this is:

$$R_{rn}(i) = R_{rn}(i-1) + (R_{ln}(i-1) + R_{lb}(i-1)) * 0.5 *$$

$$(C_{rn}(i) + C_{rn}(i-1)) * FPD(i) / (1 - CFP(i-1))$$

where:

$R_{rn}(i)$ is the interval conditional probability of rupture-no bypass for rapid pressure rise for pressure interval i;

$R_{ln}(i)$ is the interval conditional probability of leak-no bypass for rapid pressure rise for pressure interval i;

$R_{lb}(i)$ is the interval conditional probability of leak-bypass for rapid pressure rise for pressure interval i;

CFP(i) is the cumulative failure probability for all failure modes for pressure interval i;

FPD(i) is the failure probability density for all failure modes for pressure interval i;

and

$C_{rn}(i)$ is the conditional failure probability for rupture-no bypass for pressure interval i.

Analogous equations are used to find the interval conditional probabilities of rupture-bypass (R_{rb}) and catastrophic rupture (R_{cr}) for fast pressure rise. The total remaining leak fraction (R_{lk}) is then found from:

$$R_{lk}(i) = 1 - R_{rn}(i) - R_{rb}(i) - R_{cr}(i).$$

The total leak fraction is split among leak-no bypass and leak-bypass by the same ratio as the original conditional probabilities for that interval.

Table 5-10 shows the failure mode probabilities for rapid pressure rise for a failure pressure of 65 psig. The entry for rupture-no bypass for a load pressure of 70 psig is 0.056 as calculated above.

Successive applications of the equations discussed above determine the entries for each row based on the row above and the entries in Table 5-7. Zeros have been entered for the failure mode probabilities in Table 5-7 where the load pressure is below the failure pressure. In a few rows of Table 5-7, the failure mode probabilities add to 0.999 or 1.001 instead of 1.000. This is due to roundoff error in the program used to generate Table 5-10.

After studying Table 5-10 some readers have inquired why the failure mode probabilities don't go to the upper limit values shown in Table 5-7. That is, why don't the entries for 100 to 120 psig in Table 5-10 closely resemble the entries for 100 to 120 psig in Table 5-7? The answer is that the results shown in Table 5-10 come from a much different type of calculation. For rapid pressure rise, of the fraction of leaks that are still leaks at 110 psig, and for which an additional failure is calculated at 110 psig, 97.9% go to catastrophic rupture as indicated in Table 5-7. Table 5-10 shows the results of working up pressure from 65 psig to the load pressures shown in the left column. Ruptures are non-zero for 70 and 75 psig, so the rupture probability for 120 psig in Table 5-10 cannot be zero as it is in Table 5-7.

Table 5-10
Failure Mode Probabilities for Rapid Pressure Rise
Failure Pressure = 65 psig

Pressure (psig)	Cumulative Failure Probability	Failure Prob. Density	Interval Conditional Probabilities: Leak No Bypass	Leak Bypass	Rupture No Bypass	Rupture Bypass	Catastrophic Rupture
20	0.000	0.000	0.000	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30	0.018	0.018	0.000	0.000	0.000	0.000	0.000
35	0.038	0.020	0.000	0.000	0.000	0.000	0.000
40	0.060	0.022	0.000	0.000	0.000	0.000	0.000
45	0.083	0.022	0.000	0.000	0.000	0.000	0.000
50	0.124	0.041	0.000	0.000	0.000	0.000	0.000
55	0.197	0.073	0.000	0.000	0.000	0.000	0.000
60	0.395	0.198	0.000	0.000	0.000	0.000	0.003
65	0.527	0.132	0.018	0.177	0.050	0.050	0.704
70	0.706	0.179	0.122	0.023	0.056	0.053	0.748
75	0.780	0.074	0.001	0.116	0.059	0.053	0.771
80	0.833	0.054	0.087	0.002	0.059	0.054	0.799
85	0.878	0.044	0.066	0.000	0.059	0.054	0.822
90	0.922	0.044	0.043	0.000	0.059	0.054	0.845
95	0.948	0.027	0.029	0.000	0.059	0.054	0.859
100	0.975	0.026	0.014	0.000	0.050	0.054	0.873
105	0.987	0.013	0.007	0.000	0.059	0.054	0.880
110	0.994	0.006	0.004	0.000	0.059	0.054	0.884
115	0.997	0.003	0.002	0.000	0.059	0.054	0.886
120	1.000	0.003	0.000	0.000	0.059	0.054	0.887

Individual Elicitations f Issue 5

Expert A's Elicitation

Containment Failure at Sequoyah Due to Static Pressure

Description of Expert A's Rationale/Methodology

Expert A considered seven failure modes or locations.

1. Membrane Failure of the Cylinder
2. Membrane Failure of the Dome
3. Buckling of the Equipment Hatch
4. Personnel Airlock
5. Pipe Penetrations
6. Electrical Penetrations
7. Anchor Bolts.

Expert A ruled out failure of the dome: since it is hemispherical and has about the same thickness as the cylinder, it will be stronger than the cylinder. Based on previous work and knowledge, he concluded that the personnel airlock would not fail before the cylinder. Only local yielding could be expected up to pressures well above the cylinder failure pressures, and the flexible seals can accommodate what yielding may occur. Since the IDCOR study showed that pipe penetrations had high safety margins, he did not consider them further. The electrical penetrations were also ruled out as a Westinghouse study showed they were good to 100 psig or more at about 340°F. Thus, the lower bound for electrical penetration failure is above the upper bound for membrane failure of the cylinder.

Details of the equipment penetration reinforcement were not available for review. Based on experience with other free-standing steel containments, Expert A expected the penetration reinforcement to be somewhat over-reinforced compared to the shell-stiffener system away from major penetrations. Also, the plate thickness is 5/8 in. to 11/16 in. in the area of the equipment hatch. This is expected to result in a stiff area around the penetration with strains significantly less than those in the 1/2-in. plate near the spring line. Consequently, leakage from the equipment penetration--hatch interface due to ovalization or other distortion is not expected to be a controlling mode of failure.

Expert A considered cylinder membrane failure, equipment hatch buckling, and anchor bolt failure in some detail.

Based on the drawing of the anchor bolts available to Expert A before the elicitation meeting, he felt the anchor bolts were likely to yield at pressures comparable with those for which cylinder failure was estimated. This would result in leakage beneath the steel containment wall, assuming fracture of the weld between the containment wall and the floor liner. At the meeting he obtained a better detail drawing of the anchor chair area, which showed that both bolt and chair were embedded in reinforced concrete. Based on this new information, Expert A decided that anchor bolt failure was negligible compared to membrane failure.

Membrane Failure of the Cylinder. Using Sandia's finite element analysis results and other similar analyses, Expert A concluded that the highest stresses and strains in the cylindrical portion of the containment will occur in the half-inch plate just below the spring line. Using actual material properties and smearing out the stiffeners, Expert A calculated a pr/t stress that was close to those obtained by the finite element analyses and concluded that the onset of general yield occurred at 58 psig. Due to biaxial strain effects and gauge effects, Expert A considered it possible that failure might not occur until 10 or even 12% strain was reached. However, he considered it much more likely that failure would occur between 1 and 5% strain.

Buckling of the Equipment Hatch. The middle of the pressure range for this failure mode is about 200 psig. This is based on Expert A's knowledge of spherical cap tests and analyses. The range is quite wide, as the buckling failure mode is associated with large variability. This is shown by the experimental data.[A-1,A-2,A-3]

Results of Expert A's Elicitation

Membrane Failure of the Cylinder. Expert A took the onset of general yield at 58 psig to be the lower bound (2% probability) for his failure curve. Assuming that failure was most likely around 3% strain, he got 80 psig as his median failure pressure. Assuming a lognormal distribution gave the following table for membrane failure of the cylinder:

Pressure (psig)	58	62	65	72	80	89	98	104	110
Cum. Distrb. Fn.	.02	.05	.10	.25	.50	.75	.90	.95	.98

The 2% failure at the general yield pressure allows for inaccuracies in the modeling, variations in material properties, localized strain concentrations, and unknown construction defects. Membrane failure in the cylinder is almost certain to be CR since the entire zone, including the stiffeners, is above general yield. That is, the stiffeners will be in the plastic region when the shell fails, so the crack will propagate right through the stiffeners. This was observed in Sandia's scale model tests.

Buckling of the Equipment Hatch. Based on the test results, Expert A placed his 2% failure value at 90 psig. He took a lognormal distribution based on 2% failure at 90 psig and 50% failure at 200 psig and got the following table:

Pressure (psig)	89	104	120	153	200	260	330
Cum. Distrb. Fn.	02	.05	.10	.25	.50	.75	.90

The upper values are, of course, not relevant here since the cylindrical shell is expected to fail well below 150 psig. Equipment hatch failure by buckling is expected to result in leakage since the tests showed that failure was due to either cracking a weld or distortion at the edge of the hatch, both of which results in leaks in the tests. There is also a non-negligible probability that buckling can occur without causing a leak. The leak resulting from hatch failure does not bypass the ice condenser since the hatch connects the upper compartment to the outside.

All Failure Modes. The cumulative distributions of the pressures for membrane failure of the cylinder and for equipment hatch buckling can be combined to give the following table:

Pressure (psig)	Cumulative Probability of Failure Cylinder	Hatch	Both
58	.02		0.02
62	.05		0.05
65	.10		0.10
72	.25		0.25
80	.50		0.50
89	.75	.02	0.76
98	.90		
104	.95	.05	0.95
110	.98		
120		.10	1.00

Probabilities for hatch failure at 98 and 110 psig were not given. Interpolation was used to create a table of total cumulative failure probability and cumulative conditional probability of failure mode for 5 psig increments. By use of the probability density, this was then converted into a table of interval conditional probability for mode as shown in Table A-1.

Expert A was fairly confident that failure could be expected between 65 and 95 psig since about 75% of his probability lay within that range. Within the range where failure was most likely to occur, CR was almost certain since membrane failure of the cylinder was by far the most likely failure mode. There are no rupture failures in Expert A's opinion.

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A-1. Y. C. Fung and E. E. Sechler, "Instability of Thin Elastic Shells," Proceedings of the First Symposium on Naval Structural Mechanics, pp. 115-168, 1960.

A-2. Handbook of Structural Stability, NACA Tech. Notes, p. 3783, 1957-1958.

A-3. S. P. Timoshenko, Theory of Elastic Stability, New York, New York: McGraw-Hill Book Company, Inc., 1936.

Expert B's Elicitation

Containment Failure at Sequoyah Due to Static Pressure

Description of Expert B's Rationale/Methodology

Several failure locations were briefly considered and then dropped from further consideration. Failure of the personnel airlock was ruled out on the basis of tests and analysis.[B-1] Failures of electrical penetrations were ruled out for the same reasons.[B-2,B-3] No information was available to allow a reasonable evaluation of the penetrations equipped with bellows. (Most if not all of the mechanical penetrations at Sequoyah are equipped with bellows.) In the absence of test results or enough information to perform a credible analysis, Expert B did not consider these expansion joints further. Thus, Expert B considered in detail three failure locations and two temperatures for one of them. He felt temperature was important only for the membrane failure of the cylindrical portion of the shell.

Failure of the cylindrical shell always results in catastrophic rupture if the failure pressure is above the 60 psig range and always results in rupture if the failure pressure is below the 50 psig range. Below 50 psig, the membrane stresses in the entire shell are still elastic which provides some assurance that crack growth can be arrested. Above 60 psig, large areas of the shell have inelastic (plastic) stresses; there would not be sufficient strength in these areas to arrest crack growth, and crack propagation leads to catastrophic rupture.

Initial failure of the equipment hatch always results in a leak. However, the leak area will increase rapidly if the pressure continues to rise. If the pressure increases a few psig above the value which caused the initial leak, the hole area will increase into the rupture region. Failure of the anchorage system could result in either a leak or a rupture, but he judged that even if a leak occurred the size of the tear would eventually increase so that a rupture would result.

Failure of the cylindrical shell will always result in bypass of the ice condenser if it is a catastrophic rupture. If cylinder failure is a rupture, then one sixth of them can be expected not to bypass the ice condenser since there is 60° of the containment wall which is not occupied by the ice condenser. Equipment hatch failure does not bypass the ice condenser due to the location of the hatch.

Anchorage failure would always result in bypass of the ice condenser if the failure always occurred at the cylinder-shell junction, since it is below the bottom of the ice condenser. However, anchorage failure may result in no failure, or only a negligible failure, at this location. Instead the anchorage failure may precipitate failure elsewhere in the shell. Anchorage failure will allow the shell to move up considerably, and this vertical movement may well result in failure of the cylindrical shell at some penetration or stiffener plate where there is resistance to this upward motion. Thus it is impossible to say where the failure might occur.

This being the case, the anchorage failures have been divided evenly between bypass and no bypass of the ice condenser.

Results of Expert B's Elicitation

Membrane Failure of the Cylinder. For failure of the cylindrical shell, Expert B concluded that failure was most likely in the 1/2-in. plate just below the spring line. For failure at this location, about elevation 771 ft, he gave the following results of his calculations:

	Pressure(psig)		
Cumulative Probability	500°F	300°F	Response of the Containment
0.00	32	35	General yield ignoring stiffeners
0.05	48	53	General yield including stiffeners
0.50	58	60	2% equivalent membrane strain
0.80	72	72	5% equivalent membrane strain
0.99	80	80	10% equivalent membrane strain
1.00	95	96	Ultimate strain of material

Expert B checked his calculations with those of the Ames Laboratory[B-4] for the Sequoyah containment. When adjusted for material properties and temperature, the comparison was good. The table above contains two values for pressure; one assuming the containment is around 300°F or lower and the other assuming the containment is around 500°F. The higher temperature values have not been used because the bulk metal temperature never reaches 500°F as explained above (see page 5.5-2). Membrane failure of the cylinder is essentially certain by 80 psig for either temperature.

Hatch Ovalization. Expert B felt that hatch failure would occur due to ovalization. Analytical predictions of hatch ovalization failure have matched the test results very well,[B-5] so there is little uncertainty in this failure mode. This failure mode occurs because the cylindrical sleeve, which is welded to the containment shell, is distorted into an oval shape as the shell moves outward with increasing internal pressure. The hatch itself keeps its circular shape. By 2.5 to 3% strain, the sleeve is so ovalized that the sleeve flange is completely inside the hatch flange at the top and bottom and the sleeve flange is completely outside the hatch flange at the sides. Thus, this type of failure is completely independent of the gasket condition, and it will continue to grow in area as the hoop strain increases. He was certain that this ovalization would result in development of a leak when the free-field hoop strain in the cylindrical shell at the elevation (741 ft) of the center line of the equipment hatch reached about 2.7%. Expert B gave the following table of cumulative probability of leak as a function of strain:

Strain (%)	Cumulative Failure Probability	Pressure (psig)
2.4	0.01	66.7
2.5	0.05	
2.6	0.25	
2.7	0.50	
2.8	0.75	
3.0	0.90	
3.2	0.99	70.2

At 300°F, at elevation 741 ft, the free field hoop strain is 2% at 65 psig and 5% at 78 psig. The pressures for the other strain values above may be obtained by linear interpolation. Thus, Expert B expects a leak due to the hatch ovalization to occur around 68 psig and is certain it will have developed by 70 psig. The leak will be large enough to be denoted a rupture by the time 75 or 80 psig is reached. Catastrophic rupture will not result from this failure mode.

Anchorage Failure. Failure of the anchorage system affects containment integrity indirectly. As the bolts begin to yield, the knuckle could become distressed, leading to a leak. As significant yielding of the bolts occurs, significant vertical motion of the containment shell becomes increasingly probable. This motion is resisted by the penetrations, which could lead to a rupture. The analysis of this failure mode is subject to great uncertainty because it is indirect, i.e., it is based on the response of a component, which is not part of the pressure boundary.

For failure of the anchorage system, Expert B gave the following results of his calculations and a study by the Ames Laboratory:[B-1]

Cumulative Probability	Pressure (psig)	Response
0.00	60	None
0.10	65	Onset of yielding in the bolts
0.80	80	Bolts fail (nominal)
0.95	100	
1.00	135	Anchor rings pull out of concrete

Leaks resulting from anchorage failure occur at the knuckle and therefore always bypass the ice condenser. The rupture failure could take place at or around any penetration. In the absence of any further information, half the ruptures are assumed to bypass the ice condenser and half are assumed not to bypass it. Failures at the lower pressures result in leaks and failures at the higher pressures result in ruptures. The dividing line between leak and rupture is around the 70 to 75 psig range.

<u>All Three Failure Modes</u>. A table listing the failure probability as a function of pressure for 5 psig increments for all three failure locations can now be constructed:

	Cylinder Shell			Hatch Failure			Anchorage Failure		
Press. (psig)	Cum. Prob.	Cond. Rupt	Prob. CR	Cum. Prob.	Cond. Leak	Prob. Rupt.	Cum. Prob.	Cond. Leak	Prob. Rupt.
30	0.00	1.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0
35	0.005	1.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0
40	0.006	1.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0
45	0.008	1.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0
50	0.01	0.8	0.2	0.0	1.0	0.0	0.0	1.0	0.0
55	0.10	0.3	0.7	0.0	1.0	0.0	0.0	1.0	0.0
60	0.50	0.0	1.0	0.0	1.0	0.0	0.0	1.0	0.0
65	0.62	0.0	1.0	0.01	1.0	0.0	0.10	1.0	0.0
70	0.75	0.0	1.0	0.99	0.8	0.2	0.25	0.7	0.3
75	0.90	0.0	1.0	1.0	0.2	0.8	0.50	0.3	0.7
80	0.99	0.0	1.0	1.0	0.0	1.0	0.80	0.0	1.0

The hatch failures never result in bypass of the ice condenser. Leakage failures of the anchorage always result in bypass of the ice condenser and rupture failures of the anchorage are equally split between bypass and no bypass. The cylinder failures which result in rupture are split 5 to 1 in favor of bypass based on geometrical considerations. (Of the upper wall of the cylindrical shell, 300° is within the ice condenser and 60° is not. Failure within the ice condenser is assumed to result in bypass. Failure is considered equally likely for all segments.)

By assuming that the failures at the three locations are independent, a single table giving the total cumulative failure probability for all locations as a function of pressure can be formed. The method used was briefly explained in the Aggregation section above. The result is Table 5-8. Table 5-8 and its derivation were reviewed by Expert B.

Rupture or catastrophic rupture is possible above the pressure where hatch ovalization leakage is certain because the pressure rise may be too rapid to be arrested by this failure mode. The definition of a leak is that the containment does not depressurize to about atmospheric pressure in less than 2 h. For pressure rises resulting from deflagrations or deflagrations accompanied by direct heating, rise times on the order of a few seconds are expected. For loads due to these events, a leak will not arrest the pressure rise; pressure rise will be arrested only by development of a rupture or a catastrophic rupture.

Expert B felt strongly that the type of containment loading should be taken into account when using his evaluation of containment performance. His primary concern was the treatment of leaks, and the possibility of leaks increasing in area to become ruptures, for the scenarios with a fast pressure rise.

The conclusions of Expert B are shown in Table 5-2 through 5-5. His median failure value is 60 psig. All failures at this pressure are catastrophic ruptures since failure of the cylindrical shell is the only location at which Expert B feels failure is possible at this pressure. Failures below 50 psig are certain to be ruptures since Expert B did not believe leaks were a credible failure mode for failure of the cylindrical shell. Above the 60 psig median pressure, leaks, ruptures, and catastrophic ruptures are possible. Although this seems counter-intuitive at first, it is a direct result of Expert B's conclusion that the lowest pressures at which hatch ovalization and anchorage failure could occur are higher than the pressures at which shell failure is possible.

REFERENCES

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B-2. D. B. Clauss, "Comparison of Analytical Predictions and Experimental Results for the 1:8-Scale Steel Containment Model Pressurized to Failure," NUREG/CR-4209, SAND85-0679, Sandia National Laboratories, July 1985.

B-3. L. Greimann et al., "An Evaluation of the Effects of Design Details on the Capacity of LWR Steel Containment Buildings," NUREG/CR-4870, SAND87-7066, Sandia National Laboratories, May 1987.

B-4. D. B. Clauss, "An Evaluation of the Leakage Potential of a Personnel Airlock subject to Severe Accident Loads," Trans. of the 9th Int. Conf. on Structural Mechanics in Reactor Technology, Vol. J, pp. 147-152, August 17-21, 1987.

B-5. J. D. Keck and F. V. Thome, "Electrical Penetrations Assemblies Severe Accident Testing," SAND86-0703C, Sandia National Laboratories, 1986.

Expert C's Elicitation

Containment Failure at Sequoyah Due to Static Pressure

Description of Expert C's Rationale/Methodology

Expert C considered all three cases to be equivalent, but did provide a separate curve for the high temperature case. He considered five failure modes separately:

Mode 1: Leak resulting in No Bypass of the Ice Condenser
Mode 2: Leak resulting in Bypass of the Ice Condenser
Mode 3: Rupture resulting in No Bypass of the Ice Condenser
Mode 4: Rupture resulting in Bypass of the Ice Condenser
Mode 5: Catastrophic Rupture.

Expert C felt that failure is most likely to occur in one of two locations. In the upper compartment, failure was most likely to occur in the 1/2-in.-thick steel of the cylindrical shell just below the spring line. In the lower compartment, a crack in the weld at the point of embedment is the likely failure point. This location is felt by Expert C to be slightly more likely than the spring line location. By 75 psig, general membrane strains are such that failure will probably have occurred based on average material properties. Use of actual material properties may increase this pressure by a few psig.

Expert C arrived at the above conclusions by establishing the relative potential for failure at various locations. As indicated by IDCOR Technical Report 10.1 (Reference C-1) and test data, mechanical and electrical penetrations are not likely to fail before general structural failure. The critical buckling pressure for the hatch cover was calculated, and it was determined that the hatch cover is not likely to buckle at pressures which will cause general yielding in the upper part of the cylindrical shell. Since the cover is pressure-seated, no leakage due to opening of the flanges is expected. Design calculations and test results indicate that the personnel airlock is significantly over-designed for internal pressure and the probability of structural failure of the airlock is very remote. Again, the inner door of the airlock is pressure-seated and not likely to leak. The vessel anchorage is also over-designed and not likely to be the point of first failure. The controlling failure mechanism in the anchorage system would be the yielding of the anchor bolts. Anchor bolts are expected to start yielding at pressures which are somewhat higher than those which cause general yielding of the upper part of the cylindrical shell.

Expert C relied on published results (References C-1 through C-5) as well as his own calculations. In addition, he considered such practical factors as fabrication imperfections, material imperfections, residual stresses, etc. in determining how to distribute the failure probabilities among the various modes and locations. The location and type of hypothesized failures determined the breakdown between bypass of the ice condenser and no bypass of the ice condenser.

Results of Expert C's Elicitation

For 200 to 300°F, Expert C provided the following table giving the failure probabilities by mode and the total:

Probability of Containment Failure (200 to 300°F)

Pressure (psig)	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	All Modes
25	0.00	0.00	0.00	0.00	0.00	0.00
35	0.03	0.05	0.01	0.02	0.00	0.11
45	0.04	0.06	0.03	0.10	0.01	0.24
55	0.04	0.07	0.17	0.16	0.04	0.48
65	0.04	0.07	0.21	0.20	0.30	0.82
75	0.04	0.07	0.22	0.21	0.46	1.00

This table gives exclusive joint cumulative probabilities for the five modes. Interpolation was used to obtain the results for 5 psig intervals shown in Table C-1. The joint probabilities were converted to total conditional probabilities by assuming that the total conditional probability was proportional to the exclusive conditional probability. These probabilities were then converted to interval conditional probabilities as shown in Table 5-6 by use of the probability densities.

For temperatures around 600°F in containment, Expert C calculated that the yield strength of the steel would be considerably lower than the yield strength at room temperature. However, due to warm strain hardening, the ultimate strength of material is not much affected at these temperatures. Considering these temperature effects on material properties, he provided a different table for the condition that the pressures will be concurrent with a shell temperature of 600°F. This table contains a sixth mode, thermal buckling, since Expert C concluded that this failure mode was possible at 600°F when the internal pressure was at or only slightly above ambient atmospheric pressure.

Probability of Containment Failure (600°)

Pressure (psig)	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	All Modes
0	0.00	0.00	0.00	0.00	0.00	0.25	0.25
25	0.01	0.01	0.00	0.00	0.00	0.24	0.26
35	0.05	0.06	0.03	0.05	0.00	0.16	0.35
45	0.05	0.07	0.17	0.17	0.04	0.13	0.63
55	0.05	0.07	0.20	0.20	0.28	0.12	0.92
65	0.05	0.07	0.21	0.21	0.36	0.10	1.00

The cumulative probability for the thermal buckling mode decreases as pressure increases since the internal pressure will tend to counteract the thermal stresses.

The conclusions of Expert C are shown in Tables 5-3 and 5-6. The median of his failure distribution is around 56 psig. At this pressure, rupture is the most likely failure mode. Expert C was virtually certain that the containment would have failed by 75 psig.

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C-2. "Sequoyah Nuclear Power Plant, Final Safety Analysis Report," Sections 3.8.1 and 3.8.2, Tennessee Valley Authority, Knoxville, TN, 1974.

C-3. U.S. Nuclear Regulatory Commission, "Safety Evaluation Report Related to the Operation of Sequoyah Nuclear Plant Units 1 and 2," NUREG-0011, Supplement 6, pp. 22-15 and 22-16, Washington, D.C., 1982.

C-4. W. Sebrell, "The Potential for Containment Leak Paths through Electrical Penetration Assemblies under Severe Accident Conditions," NUREG/CR-3234, SAND83-0538, Sandia National Laboratories, 1983.

C-5. D. B. Clauss, "Comparison of Analytical Predictions and Experimental Results for the 1:8-Scale Steel Containment Model Pressurized to Failure," NUREG/CR-4209, SAND85-0679, Sandia National Laboratories, 1985.

5.6 Issue 6: Sequoyah Containment Failure Due to Detonation

Experts consulted: Charles Miller, City College of New York; Walter A. von Riesemann, Sandia National Laboratories; Don Wesley, IMPELL.

Issue Description

What distributions characterize the uncertainty in containment failure due to detonations in the ice condenser, and what is the likely failure site? What distributions characterize the uncertainty in ice condenser bypass due to mechanical displacement of the ice following a hydrogen detonation? The variables elicited are the probability of containment failure and the location of the failure as a function of applied impulse, and the probability of ice condenser bypass as a function of applied impulse.

Summary of Results

Expert A considered the following failure modes for the Sequoyah response to detonation: (1) anchor bolt failure that results in a leak or rupture near the base of the containment, (2) membrane failure in the containment cylinder area, and (3) buckling failure of the cylinder due to detonation at the top of the containment. In addition, the expert considered the probability of loss of ice condenser function due to detonation in the ice condenser.

The expert concluded that buckling would not be reached before blowout of the cylinder and provided distributions for the anchor bolt failure mechanism, membrane failure of the containment cylinder above the ice condenser, membrane failure of the containment cylinder in the lower part of containment, and loss of the ice condenser function.

Expert B analyzed the containment as an axisymmetric ring. For the wall of containment above the ice condenser, a single panel was analyzed for membrane and bending stress. Bending stress was found to be a minor contributor to failure and the plate was found to be fairly strong in bending action (well above the range for hoop failure). For detonation within the ice condenser or upper plenum, only panel response needed to be considered and the expert considered the membrane response of the plate.

The expert concluded that a path would be opened through the ice condenser under any detonation conditions.

Expert C applied a simplified analysis method which, in essence, equates the kinetic energy of the structure to the strain energy. He noted that tests conducted on steel containments showed that failure generally occurred when the global strain reached approximately 2%. Although the steel has a higher capacity in uniaxial tension, the existence of biaxial stress and the presence of strain risers reduce the effective capacity to about 2%. Other tests have shown that strain rate effects (dynamic loading) can increase the strength of steels by a factor of 1.3. Other variables that can affect the failure strain are the yield stress of the steel, strain rate, strain to failure, effect of temperature on mechanical properties, and the loading function. Based on these factors, Expert C multiplied his best estimate (2% strain) failure impulse estimates by factors of 0.41 and 1.97 to get approximate lower and upper bounds.

Expert C's calculations for the upper plenum and for the ice condenser differed mainly in the need to take the effect of the insulating wall panels into account for the detonations in the ice condenser. The impulse needed to fail the steel shell was estimated as described above. It was estimated that the honeycomb insulating panel would require a constant pressure three times the design pressure to crush The crane wall consists of at least 3 ft of reinforced concrete. Expert C calculated that the failure impulse for the crane wall would be greater than that for the containment shell.

All of the panel members provided information in the same form, that is, tables of cumulative failure probability as a function of applied impulse. The cumulative failure probability corresponding to some impulse, I, is the probability that the structure will fail at or below the indicated impulse. All three experts gave distributions for failure impulse in both the upper pleneum and the ice condenser. In addition, Expert A provided a distribution for failure of containment via anchor bolt failure caused by a detonation in the dome, and Expert B provided a distribution for failure in the containment wall above the plenum. However, subsequent to elicitation of the structural response experts, the containment loading panel determined that a detonation in the containment dome was not credible; therefore, distributions based on detonations in the dome have not been reduced. Possible failure of the containment dome due to deflagrations in the dome is considered under Structural Issue 6--Containment Failure at Sequoyah Due to Static Pressure.

The individual experts' distributions are shown in Tables 6-1 through 6-3. None of the experts provided impulse values for the endpoints of their distributions; these were derived by extrapolation and checked with the experts. Table 6-4 and Figure 6-1 show the aggregate distributions for failure of the upper plenum. Table 6-5 and Figure 6-2 show the aggregate distributions for failure of the ice condenser.

Table 6-1
Distributions for Expert A

Failure of Upper Plenum:

Impulse (kPa-s)	Cumulative Failure Probability
3.70	0.00 (Extrapolated)
4.48	0.02
5.65	0.05
6.90	0.10
9.45	0.25
13.45	0.50
16.07	0.75
18.62	0.90
20.69	0.95
22.76	1.00 (Extrapolated)

Failure of Ice Condenser:

Impulse (kPa-s)	Cumulative Failure Probability
6.50	0.00 (Extrapolated)
7.93	0.02
10.07	0.05
12.27	0.10
17.24	0.25
24.82	0.50
30.34	0.75
36.54	0.90
40.68	0.95
44.82	1.00 (Extrapolated)

Table 6-2
Distributions for Expert B

Failure of Upper Plenum:

Impulse (kPa-s)	Cumulative Failure Probability
0.46	0.00 (Extrapolated)
2.07	0.05
6.90	0.20
12.41	0.50
44.82	0.95
48.42	1.00 (Extrapolated)

Failure of Ice Condenser:

Impulse (kPa-s)	Cumulative Failure Probability
5.18	0.00 (Extrapolated)
6.90	0.01
13.79	0.05
20.68	0.11
27.58	0.25
34.48	0.50
41.37	0.72
48.26	0.89
55.16	0.95
62.06	0.99
63.78	1.00 (Extrapolated)

Table 6-3
Distributions for Expert C

Failure of Upper Plenum:

Impulse (kPa-s)	Cumulative Failure Probability
0.69	0.00
1.38	0.01
3.45	0.50
6.90	0.90
10.34	1.00

Failure of Ice Condenser:

Impulse (kPa-s)	Cumulative Failure Probability
0.69	0.00
1.38	0.01
4.83	0.50
9.66	0.90
13.79	1.00

Table 6-4
Aggregate Distribution for Failure of Upper Plenum

Impulse (kPa-s)	Cumulative Failure Probability
4.600E-01	0.000E+00
6.900E-01	2.381E-03
1.380E+00	1.286E-02
2.070E-00	7.444E-02
3.450E+00	1.976E-01
3.700E+00	2.099E-01
4.480E+00	2.548E-01
5.550E+00	3.221E-01
6.900E+00	4.000E-01
9.450E+00	5.210E-01
1.034E+01	5.643E-01
1.241E+01	6.450E-01
1.345E+01	6.715E-01
1.607E+01	7.699E-01
1.862E+01	8.287E-01
2.069E+01	8.550E-01
2.276E+01	8.812E-01
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4.842E+01	1.000E+00

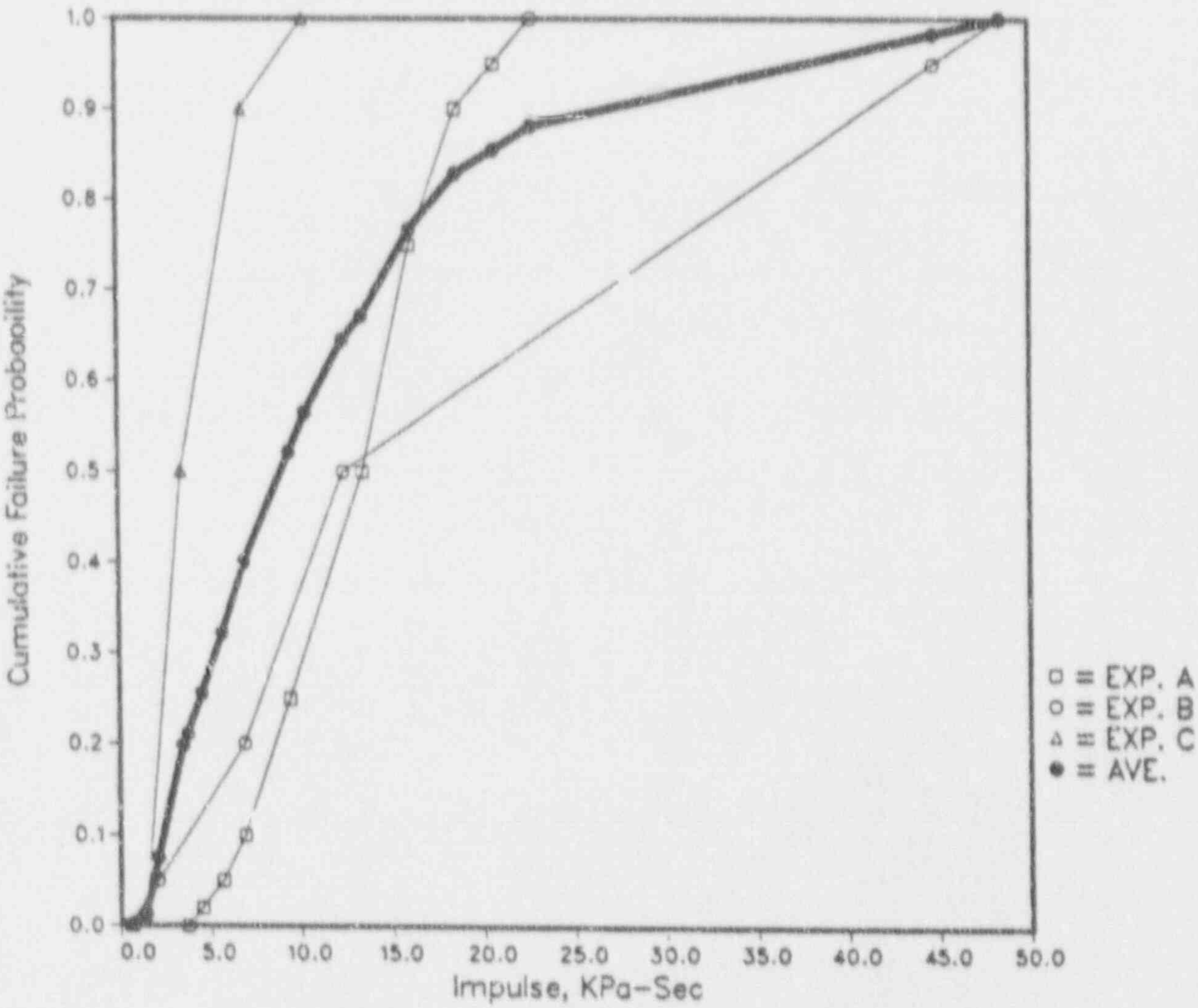

Figure 6-1. Failure of the Upper Plenum Due to Detonation.

Table 6-5
Aggregated Distribution for Failure of Ice Condenser

Impulse (kPa-s)	Cumulative Failure Probability
6.900E-01	0.000E+00
1.380E+00	3.333E-03
4.830E+00	1.667E-01
5.180E+00	1.763E-01
6.500E+00	2.153E-01
6.900E+00	2.290E-01
7.930E+00	2.642E-01
9.660E+00	3.234E-01
1.007E+01	3.294E-01
1.227E+01	3.681E-01
1.379E+01	3.986E-01
1.724E+01	4.433E-01
2.068E+01	4.912E-01
2.482E+01	5.64E-01
2.758E+01	6.250E-01
3.034E+01	7.000E-01
3.448E+01	7.834E-01
3.654E+01	8.219E-01
4.068E+01	8.827E-01
4.137E+01	8.928E-01
4.482E+01	9.350E-01
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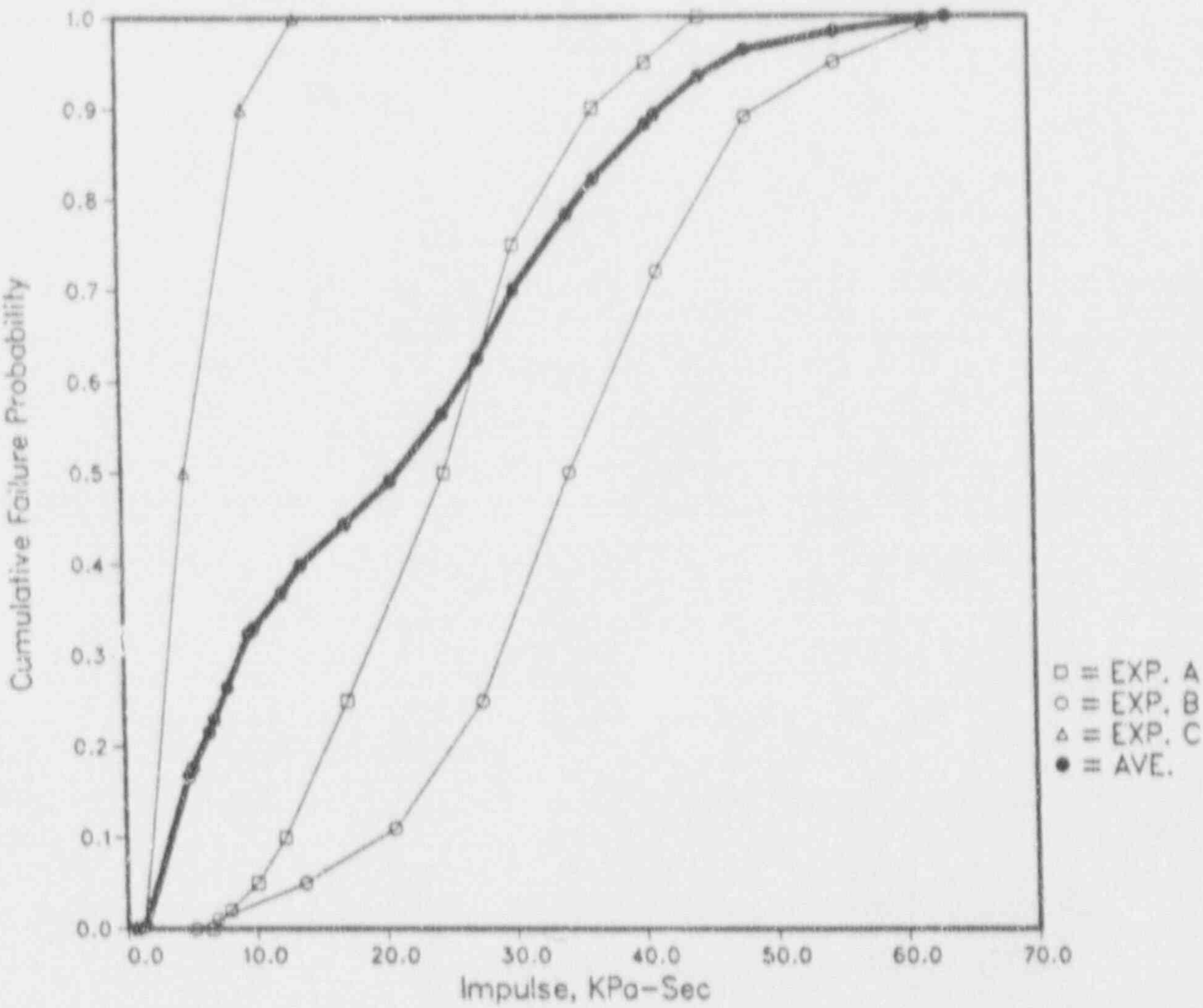

Figure 6-2. Failure of Ice Condenser Due to Detonation.

Individual Elicitations for Issue 6

Expert A's Elicitation

Sequoyah Containment Failure Due to Detonation

Determination of Expert A's Rationale/Methodology

Expert A considered the same failure modes which he considered for static failure plus panel failure of the ice condenser and buckling of the cylinder at its base. In particular, these modes are:

Anchor bolt failure. This mode results in a leak or rupture near the base of the containment that produces ice condenser bypass. Static failure occurs at about 135 psig and is controlled by brittle failure of the concrete surrounding the anchor bolt chairs. This failure mode provided a fairly tortuous leak path for fission products. The Expert had difficulty estimating what the dynamic load factor would be. He did not have an accurate estimate of the containment axial (vertical) frequency. An estimate of the frequency was developed which turned out to be in the same range as the expected pulse (0.01 to 0.003 s). Dynamic load factors can vary widely. Load factors of 1.25 to 1.5 can result from sharp pressure spikes dropping off linearly (an essentially triangular pulse shape) or faster. A square pressure pulse could produce a load factor of 2.0. On the other hand load factors of 0.4 could occur when the pressure pulse doesn't excite any of the natural periods of the structure.

Once brittle failure of the concrete occurs, elastic deformations can occur in the bolts of about 0.3 in. There is also some probability of fracture of the 3/8-in. fillet weld of the liner to the shell (estimated to be in the range of 0.5), even for low strains in the bolts. Plastic failure of the bolts could occur above the concrete failure pressure (about 135 psig). This failure could occur without fracturing the bolts. The liner could then fracture. At that point it would only require about 2 psig to lift the shell. At higher pressures, a ductility of the range 10 to 15 is expected, based on 13% strain in 8-in. gauge length. One can derive (from Biggs) the peak pressure that the bolts could withstand from:

peak pressure = R/0.1 to R/0.35,

where R is the bolt resistance. The bolt strength was increased about 1.48 to 1.58 above the static strength predicted by the equation above, based on Kinney & Graham. This results in Table A-1.

Membrane failure in the containment cylinder area. The Expert considered both the impulse-and-strain-energy-effects approach and the vibration (DAF) approach. Both approaches yielded the same order of magnitude predictions for radial (breathing mode) detonations in the 1/2-in. containment wall above the ice condenser and the 5/8-in. ice condenser wall. He used the same strain criteria for failure as in the static case but increased the material strength (at the median of the distribution) to account for the rapid strain rate effects. For the mid-height region of the cylinder with the 5/8-in. ice condenser wall the Expert used the same failure requirements as for failure in 1/2-in. material. His failure probability curve for lower containment failure is similar in shape to that for upper containment failure. However, it is offset by a factor of almost two in pressure. Failure in the lower containment results in ice condenser bypass. His method resulted in predictions of failure shown in Table A-2 for failure in the upper cylinder (1/2-in. wall). In the case of failure in the containment cylinder Expert A was uncomfortable with having to estimate his lower bound because there tend to be lower bounds on some parameters such as material strength, etc., that the tail of a lognormal distribution does not appropriately characterize. Also, the level of analysis on which the failure distribution was based probably does not justify very low failure frequency estimates. Lognormal distributions were used for making his probability estimates for a variety of reasons. Since material properties tend to be lognormal, he assumed the pulse duration was lognormally distributed, etc.

Predictions for failure in the mid-height to lower part of the containment are shown in Table A-3. Failure in the mid-height to lower part of the containment results in ice condenser bypass. Membrane failures will always result in leaks.

The spherical dome of the containment has a somewhat lower DAF than other parts of the containment, so containment failures will be controlled by failure in the cylindrical sections.

<u>Buckling failure of the cylinder due to detonation at the top of the containment</u>. The Expert made an estimate of the lateral frequency and found that the DAF would be < 1 for wide frequency variations. The Expert also checked the buckling strength using NASA SP-8007, neglecting pressure strengthening. He assumed an impulse on a half cylinder for several assumed lengths over which the pressure acts. He concluded that buckling would not be reached before blowout of the cylinder.

Expert A did not investigate dynamic buckling of the equipment hatch or electrical penetrations.

In addition to the three containment failure modes mentioned above, Expert A considered the probability of loss of ice condenser function due to detonation in the ice condenser. Loss of ice condenser function was defined as sufficient disarray of the ice baskets and the insulation panels to form a flow channel through the ice condenser for the steam. The Expert called this failure ice condenser panel blowout. He based his results for the estimated capacity of the Sequoyah ice condenser on the Sequoyah final safety analysis report (FSAR) information: a 9 psig design pressure or 1.5 x DAF x 1.4 = 18.9 psig (for 1.4 M.S.) From an elastic 1.5 DAF, he estimated that t/T = 0.5 to 2 and μ = 10-20 for failure where:

- t = duration of the pulse
- T = natural period of the (elastic) system
- μ = ductility.

Table A-4 shows the estimated failure probabilities.

Results of Expert A's Elicitation

The Expert expressed his failure probabilities in terms of the reflected pressure. The reflected pressure is typically 2.3 x incident pressure. He translated reflected pressure into impulse for pulse durations of 3 to 10 ms. If the Containment Loads Expert Panel predicts pulse durations longer than 20 ms, his pulse durations should be lengthened.

The Expert's lower probability bounds were created by assuming the most benign conditions that he could imagine. He then calculated a median from his estimate of the most likely conditions, assumed a lognormal distribution between the 2% probability and the median, and projected to higher pressures.

The Expert provided probability distributions for three independent failure modes with three independent locations. They are shown in Tables A-1 to A-3. The probability of loss of ice condenser function due to detonation is given in Table A-4.

Table A-1
Anchor Bolt Failure (Ice Condenser Bypass)

	Leak		Rupture	
Cumulative Probability	Reflected Pressure (psig)	Impulse (psig-s)	Reflected Pressure (psig)	Impulse (psig-s)
0.02	125.0	1.25	185.0	1.0
0.05	138.0	1.26	250.0	2.0
0.10	150.0	1.27	315.0	2.0
0.25	170.0	1.28	470.0	3.0
0.50	200.0	1.3	750.0	4.0
0.75	260.0	1.32	1180.0	5.0
0.90	330.0	1.33	1790.0	6.0
0.95	380.0	1.34	2300.0	6.0
0.98	450.0	1.35		

Table A-2
Membrane Failure of the Containment Cylinder
Containment Wall Above Ice Condenser
(No Ice Condenser Bypass)

Cumulative Failure Probability (Leak)	Reflected Pressure (psig)	Impulse (psig·s)	Impulse (kPa·s)
0.00	-	-	3.70
0.02	65.0	0.65	4.48
0.05	88.0	0.82	5.65
0.10	115.0	1.00	6.90
0.25	180.0	1.37	9.45
0.5	300.0	1.95	13.45
0.75	490.0	2.33	16.07
0.90	780.0	2.70	18.62
0.95	1000.0	3.00	20.69
1.00	-	-	22.76

Table A-3
Membrane Failure of the Containment Cylinder
Lower Part of Containment
(Ice Condenser Bypass)

Cumulative Failure Probability (Leak)	Reflected Pressure (psig)	Impulse (psig·s)	Impulse (kPa·s)
0.0	-	-	6.50
0.02	115	1.15	7.93
0.05	160	1.46	10.07
0.10	210	1.78	12.27
0.25	330	2.50	17.24
0.50	560	3.60	24.82
0.75	940	4.4	30.34
0.90	1500	5.3	36.54
0.95	1950	5.9	40.68
1.00	-	-	44.82

Table A-4
Ice Condenser Panel Blowout
(Loss of Ice Condenser Function)

Cumulative Failure Probability (leak)	Reflected Pressure (psig)	Impulse (psig-s)
0.02	22.0	0.22
0.05	26.0	0.24
0.10	30.0	0.26
0.25	38.0	0.29
0.50	50.0	0.33
0.75	65.0	0.34
0.90	83.0	0.35
0.95	97.0	0.36

In Tables A-1 and A-3 the Expert's predictions have been extrapolated to 0 and 1.0 probability using a liner extrapolation from probability 0.02 and 0.95, respectively.

After subsequent discussions with the experts on the Containment Loads Panel it was determined that it would be impossible that a detonation could occur that would load the containment anchor bolts. A detonation in the dome of the containment would be required. Thus, the anchor bolt failure mode was not included in the calculation of containment failure probability. Also, at the suggestion of the Containment Loads Panel, HECTR calculations were made to determine the efficiency of the ice condenser when the ice baskets were moved aside to form a flow channel. They indicated that even with considerable disarray of the ice condenser baskets, the ice condenser could maintain its function. Thus the Expert's prediction of ice condenser failure (which assumed that function was lost if the ice baskets were moved enough to form a gas flow channel) was not used in the plant analysis.

Sources of Uncertainty

The sources of uncertainties in Expert A's calculation of membrane failure in the lower part of the containment include: (a) material properties (static properties and strain rate effects), (b) the location of the detonation (he usually assumed that the detonation occurred in the worst place), (c) the duration of the impulse, (d) the natural frequency of the modes that are being excited, and (e) the ductility or strain at which failure occurs.

Suggested Methods for Reducing Uncertainty

Expert A's estimates of the ice condenser panel's blowout probabilities would be improved if he had more information about the panels than can be found in the Final Safety Analysis Report. He would like to have structural drawings to see how the corrugated panels are welded together, etc. The estimates of failure pressure are only order-of-magnitude estimates. He couldn't calculate the dynamic amplification, so he used what was in the FSARs and assumed fairly high ductilities for the steel plate.

Correlations with Other Variables

Possible correlations with other variables being elicited were not discussed.

Expert B's Elicitation

Sequoyah Containment Failure Due to Detonation

Determination of Expert B's Rationale/Methodology

Expert B analyzed the containment as an axisymmetric ring, and first considered the internal pressure to just cause yielding, which was calculated as 54 psig. He considered resistances in the range of 40 to 75 psig, pulse amplifcation factors of 0.5 to 5, and pulse durations of 0.001 and 0.015 s. The range of impulses calculated for the containment wall above the plenum was 0.120 to 3.04 psi-s (0.83 to 2.10 kPa-s). Failure was considered possible if there were a strain of 2%.

For the wall of containment above the ice condenser, a single panel was analyzed for membrane and bending stress. Bending stress was found to be unlikely to cause failure, and the plate was relatively strong in membrane action; impulses of interest from 1 to 30 psi-s, well above the range for hoop failure.

For the contents of the ice condenser, he concluded that the Sequoyah FSAR's value of 1 psi with a factor of safety of three implied 3 psi for yield of the structure. If a factor of ten for inelastic response is assumed, the structure could handle at most a dynamic pressure of 30 psi. He therefore concluded that, for almost any detonation, a path would be opened through the ice condenser; about 12 baskets could be displaced with no difficulty.

For detonation within the ice condenser or upper plenum, only panel response needs to be considered (axisymmetric loading is not possible). He considered the membrane response of the plate, with amplication.

This Expert considered the effects of a detonation within the upper plenum, allowing the upper end of the plenum to move outwards by a factor of five. For detonation in the upper plenum, the pulse amplication factor for the containment wall was reduced by a factor of five for the upper end, in the middle region by a factor of four, and at the lower end by a factor of three. The reasons for reducing the pulse amplification factors are that reflections are less likely to occur.

Results of Expert B's Elicitation

Containment wall above plenum

Side-On Impulse (psi-s)	Side-On Impulse (kPa-s)	Probability of Failure
0.1	0.69	0.00
0.25	1.72	0.20
0.50	3.44	0.55
0.75	5.17	0.70
1.00	6.90	0.83
1.25	8.62	0.93
1.50	10.34	0.99
1.75	12.07	1.00

Containment wall in upper plenum

Side-On Impulse (psi-s)	Side-On Impulse (kPa-s)	Probability of Failure
0.30	2.07	0.05
1.00	6.90	0.20
1.80	12.41	0.50
6.5	44.82	0.95

Containment wall in ice condenser

Side-On Impulse (psi-s)	Side-On Impulse (kPa-s)	Probability of Failure
1.0	6.90	0.01
2.0	13.79	0.05
3.0	20.68	0.11
4.0	27.58	0.25
5.0	34.48	0.50
6.0	41.37	0.72
7.0	48.26	0.89
8.0	55.16	0.95
9.0	62.06	0.99

Sources of Uncertainty

The loading is not at all well known. Neither the location of initiation, nor the pulse shape, duration, and reflections are known at all. As a result, the uncertainty band has to be very broad to cover all possible loadings. Other sources of uncertainty are the resistance and the strain at failure. There is great uncertainty about the structural details of the ice baskets. However, the range of impulses from any reasonable detonation is probably well above the strength of the baskets.

Expert C's Eli.·tation

Sequoyah Containment Failure Due to Detonation

Determination of Expert C's Rationale/Methodology

Expert C nctad that the final safety analysis report (FSAR) indicates that the walls of the ice condenser are composed of corrugated steel insulating wall panels designed to withstand 19 psig. The design concern was the case where the pressures would be higher outside the ice condenser than inside the ice condenser. As the FSAR states that the panels are "...attacheo to the containment shell by studs welded to the shell," it appeared reasonable that these insulating panels would also withstand 19 psig when the pressure is higher inside the ice condenser than outside it.

These insulating panels do not extend into the upper plenum. Thus the calculation is different for a detonation in the ice condenser proper than for a detonation in the upper plenum. The impulse from a detonation in the ice condenser would have to crush the insulating panel attached to the containment shell as well as fail the shell itself. The impulse from a detonation in the upper plenum would only have to fail the shell itself. While the walls of the upper plenum are obviously insulated, there is no indication that this insulation has any significant strength in itself.

Expert C assumed that the detonation could occur at any point in the ice condenser or the upper plenum. He further assumed that only a single detonation would occur and that the strength of the plenum itself is negligible. A detonation in the ice condenser could cause failure of the containment shell, the crane wall, or the ends of the ice condenser. (The ice condenser occupies 300° of the space between the crane wall and the steel containment shell. The "ends" of the ice condenser are the walls that run from the crane wall to the containment shell at each end of the 300° occupied by the ice condenser.)

Due to the uncertainty in the definition of the loading (spatial and temporal), a simplified method developed for weapons work was utilized. In essence, this method equates the kinetic energy of the structure to the strain energy. The results of this approximate method compared well with earlier calculations that utilized a different method.

Detonation in the Upper Plenum. Examination of the Sequoyah FSAR convinced Expert C that the upper plenum has essentially no strength and that he need consider only the containment shell. At the elevation of the upper plenum the shell is 0.5 in. thick. The minimum yield strength for the steel is 32 ksi; the upper bound is 47 ksi. On the basis of the tests conducted on steel containments, a global strain of 2% was considered to be failure. While the material has a higher capacity in uniaxial tension, due to biaxial stress conditions, and, more importantly, to strain risers, the 2% value has been found to be reasonable. There is no effect on the material properties due to temperature. Other tests have shown that strain rate effects (dynamic loading) can increase the strength of steels by a factor of 1.3.

The impulse required to cause failure is calculated by equating the kinetic energy to the strain energy. Limitations of this technique are discussed in Experts C's detailed notes. The calculated midpoint failure impulse for detonation in the upper plenum is 0.50 psi-s. The factors that could modify this result are the yield stress of the steel, strain rate, strain to failure, effect of temperature on mechanical properties, and the loading [illegible]. The total effect is that the "best estimate" results are multi- [illegible] factors of 0.41 and 1.97 to get approximate lower and upper [illegible]

[illegible] ime of the detonation in the upper plenum, the doors from the ice [illegible] r would be open. No attempt was made to calculate the effect of an [illegible] impulse on the ice baskets.

Detonation in the Ice Condenser. All sides of the ice condenser are made of insulating wall panels made from corrugated sheet steel. The panels are designed for a pressure of 19 psig. They are attached to the crane wall and the containment shell. Three analyses were performed: (1) failure of the wall panel and the containment shell; (2) failure of the wall panel and the crane wall; and (3) failure of only the wall panel. The third analysis applies to the failure of the ends of the ice condenser.

It appeared to Expert C that the insulating wall panel would crush like a honeycomb material, that is, the pressure required to cause crushing will be constant. He estimated that three times design pressure would be required to crush the wall panels.

For failure of the wall panel and the containment shell, Expert C calculated a midpoint failure impulse of 0.70 psi-s. The factors that could modify the results were taken to be the same as for the detonation in the upper plenum. The containment shell is 0.625 in. thick at the elevation of the ice condenser.

For failure of the wall panel and the crane wall, the situation is complicated by the fact that there is no description of the reinforcing steel in the crane wall in the Sequoyah FSAR. It is stated that the wall is designed for an internal pressure of 12 psig and for local jet forces of 100 to 300 kips. The minimum thickness of the wall is 3.0 ft. Based on this information, Expert C calculated the failure impulse for the crane wall would be greater than that for the containment shell.

For failure of only the wall panel, i.e., the failure of the ends of the ice condenser, Expert C calculated a midpoint failure impulse of 0.35 psi-s. Failure of the ends of the ice condenser would result in bypass of the ice condenser, but not containment failure. How much function of the ice condenser would be lost by failure of an end of the ice condenser would depend upon the exact failure location and size.

Effect of a Detonation on the Ice Baskets. The ice basket are cylinders approximately 12 in. in diameter and 12 ft in length. Four baskets are joined to form a column 48 ft long. The sheet steel forming the wall of the baskets are perforated: the open area is 64%. There is a lateral support for the baskets every 6 ft. This consists of a lattice frame. The frame is supported by columns at the four corners of the frame. The two interior columns at the crane wall are attached to the wall while the two outside columns next to the shell are free standing.

A detonation in the ice condenser away from the lattice frames could cause a considerable radial displacement of the ice baskets. There is approximately 2 in. between baskets, and a cumulative displacement of 16 in. could occur. The impulse required to deform the baskets is difficult to determine due to the many variables, including the strength of the ice basket when filled with ice. It was estimated that an impulse as low as 0.02 psi-s would cause a large deformation. The uncertainties involved in this estimate are great; there is no way outside of involved experiments or calculations to refine this estimate.

References and details of his calculations are contained in Expert C's detailed notes, which are not reproduced here.

Results of Expert C's Elicitation

Expert C provided 1, 50, and 90% probability values for the impulse needed to fail the containment due to a detonation in the upper plenum and for the impulse needed to fail the containment due to a detonation in the ice condenser. These values are listed in the table below. The 0 and 100% values are extrapolations which account for other uncertainties and unknown effects. These extrapolations were made by the project staff and approved by Expert C.

For the impulse needed to fail the containment due to a detonation in the upper plenum, the midpoint value was obtained by using the estimate that a 2% global strain is equivalent to failure. The 1 and 90% impulses were obtained by applying the modification factors described above. For the impulse needed to fail the containment due to a detonation in the ice condenser, the midpoint value was obtained as described above based on a 2% global strain and the need to crush the insulating wall panels. The 1 and 90% impulses were again obtained by applying the given modification factors to the strain energy.

Best Estimate of the
Impulse Needed to Fail Containment

Cumulative Probability	Detonation in the Upper Plenum (psi-s)	(kPa-s)	Detonation in the Ice Condenser psi-s)	(kPa-s)
0%	0.10	0.69	0.10	0.69
1%	0.20	1.38	0.20	1.38
50%	0.50	3.45	0.70	4.83
90%	1.0	6.90	1.4	9.66
100%	1.5	10.34	2.0	13.79

Sources of Uncertainty

The three major sources of uncertainty in any structural dynamics problem are: (1) the spatial and temporal description of the loading function; (2) the design of the structural components; and (3) the method(s) of analysis. For this issue, the usual method of analysis was modified so that a failure level was calculated instead of a response for a given load. However, this does not completely eliminate the uncertainty with respect to the load. As discussed in the section on calculations in the notes, the response (failure level) obviously depends on the full description of the load (spatial, direction, magnitude, pulse shape, etc.). The effect on the response has been estimated in the text.

Regarding uncertainty in the design of the structural components, a complete set of design drawings for the containment shell was available. Material properties for the steel shell were also available, including mill tests. However, only the details and drawings in the FSAR were available for the design of the ice condenser components (wall panels, ice baskets, and lattice frame). In particular, the details of the design of the wall panels are sketchy. No "as-built" drawings were available.

Because of the lack of detailed design drawings and due to the nature of the investigation, no detailed analyses were conducted. For example, a finite element analysis of the wall panels was not attempted. Rather, as described in the Expert's notes, a simplified method of analysis was used. This method has been used successfully in other applications, such as weapons design. Expert C concluded that the use of this simplified method was not a major contributor to the overall uncertainty.

5.7 Issue 7: Containment Failure Due to Wetwell Detonations at Grand Gulf

Experts consulted: Charles Miller, City College of New York; Subir Sen, Bechtel Corp ; Donald Wesley, IMPELL.

Issue Description

Two separate questions were asked. The first was: "What is the distribution that characterizes the uncertainty in the dynamic load in the wetwell required to produce failure of the containment for the Grand Gulf atomic power plant?" The second was: "What is the distribution that characterizes the uncertainty in the dynamic load in the wetwell required to produce failure of the structure between the wetwell and the drywell, above the suppression pool?"

The independent variables were initial leakage level in the drywell, impulse generated by the detonation and existing static pressure at the time of detonation. Three cases were initially defined.

Case 1: No existing leakage in the drywell and the wetwell is at ambient pressure at the time of detonation.

Case 2: The wetwell was preconditioned by a sustained static pressure before the detonation.

Case 3: There is an existing leak in the drywell at Levels 2 or 3, respectively. Thus, the drywell has been preconditioned by damage due to pressure pulses before the detonation.

During discussion, the three experts agreed that the range of impulses for which the existence of pre-existing leakage at Levels 2 or 3 made any difference in the containment response was so small that pre-exisitng leakage could be ignored. Thus, Case 3 is indistinguishable from Case 1 and no separate results were obtained for Case 3.

The variable elicited is the probability of a failure at a given level. Levels of failure are separately defined for the containment leakage and for suppression pool bypass.

For the containment or wetwell failure, three levels of failure were defined at first:

Level 1 is development of a leak which does not significantly exceed the technical specifications. (Leakage less than 0.5% per day.)

Level 2 is a leak having an area of approximately 0.1 ft^2.

Level 3 is a leak sufficient to depressurize the containment (area greater than 1 ft^2).

It was later determined that leakage near the design basis level was not of interest and Level 1 was eliminated.

For suppression pool bypass or drywell failure, four levels were defined:

> Level 1 is development of a leak with an area of approximately 0.017 ft^2.
>
> Level 2 is a leak with an area of approximately 0.1 ft^2.
>
> Level 3 is a leak with an area of approximately 1.0 ft^2.
>
> Level 4 is the drywell completely failed; the failure creates an escape path with an area of approximately 10 ft^2 or more.

Subsequent to the elicitation, the accident progression event tree was altered to combine Levels 3 and 4, and Level 1 was eliminated.

All three experts indicated that failure probabilities for case 2 could be obtained from the distributions for case 1 by application of the interaction factor. Thus there were no separate results given for case 2. Furthermore, case 2 was not used in the accident progression analysis. The only time the static pressure would be large enough to significantly affect the failure distribution would be during blackout accidents when the suppression pool has reached saturation temperature. In this situation, the wetwell will probably be inert due to the high steam concentration. Therefore, as case 3 was combined with case 1 and case 2 was not used, only the results for case 1 were aggregated.

Summary of Results

Tables 7-1 through 7-3 contain the containment failure distribution for the three experts. The aggregate distribution is given in Table 7-4. Tables 7-5 and 7-6 give the distributions of Experts A and B for wetwell failure or suppression pool by pass. Expert C concluded that his distribution for drywell failure (Table 7-3) applied to wetwell failures as well. The aggregate wetwell failure distributions are given in Table 7-7.

Expert A provided cumulative failure probabilities as functions of applied impulse, and conditional probabilities of failure at Levels 1, 2, and 3. The cumulative failure probability was corrected for elimination of Level 1, and the conditional probabilities for Levels 2 and 3 were renormalized. After elimination of Level 1, Expert A's cumulative distribution did not go to a high probability level. The distribution was linearly extrapolated to unit probability. For drywell failure, Expert A provided separate distributions for detonations originating in the wetwell annulus and the dome. Either ignition location is equally likely, so the two distributions were numerically averaged. Table 7-1 shows Expert A's corrected distribution for containment failure in the standard format. Table 7-5 shows Expert A's corrected distribution for drywell failure.

Expert B also provided total and conditional distributions for each level. A distribution was given for drywell failure only, with the proviso that impulse levels should be reduced by 40% for the containment wall. Expert B's conditional probabilities for Levels 3 and 4 were summed to give total probabilities for a combined Level 3 and 4. Tables 7-2 and 7-6 give the failure distributions for Expert B.

Expert C provided separate distributions for failure at Levels 2 and 3. He stated that he was unable to distinguish between the drywell and containment, and that the same distribution should apply to each. Expert C's independent distributions for each failure level were converted to a total cumulative failure probability, and conditional probabilities for each level. Table 7-3 gives Expert C's converted results for containment and drywell failure. Note that Expert C did not assume that Level 2 was more likely at low levels and Level 3 was more likely at high levels, as did the other experts. He apparently believes that Level 2 is approximately twice as likely as Level 3 at all impulse levels. The jumps in the curves are a result of the numerical conversion to conditional probabilities, and do not indicate an intention by the expert to vary the conditional probabilities.

Method of Aggregation

To make the aggregation simpler, all distributions were converted to impulse at intervals of 2.5 kPa-s. Linear interpolation was used to find dependent variables between the impulse points given by the experts, and points outside of the range given by the experts were found by linear extrapolation.

The total cumulative failure probabilities and conditional probabilities for each level were aggregated by averaging probabilities for each impulse level. The results are shown in Tables 7-4 and 7-7 and Figures 7-1 and 7-2. Figure 7-1 shows the aggregate cumulative failure probability and the aggregate conditional failure level probabilities for containment (wetwell) failure. Figure 7-2 shows analogous information for drywell failure. The conditional probabilities for each level fluctuate because of the numerical conversion procedure used on Expert C's data. The quality of the aggregated conditional probabilities can be improved if the mean value for all impulse levels is used for Expert C. The results of this smoothing procedure are shown in Figures 3 and 4.

The results from the three experts are qualitatively similar. Usually Expert B assessed a lower strength than the other experts, and Expert C assessed a higher strength, although there are exceptions for some cases and some fractiles. Expert A was generally intermediate between Experts B and C. The aggregate total cumulative failure curves are smooth and well behaved. The aggregate distributions appear to be roughly log-normal in shape.

Table 7-1
Containment Failure: Distributions for Expert A

Impulse (kPa-s)	Total Cumulative Failure Probability	Conditional Probabilities	
		Level 2 Failure	Level 3 Failure
2.5	0.073	1.000	0.000
5.0	0.272	0.937	0.063
7.5	0.533	0.856	0.144
10.0	0.606	0.715	0.285
12.5	0.679	0.573	0.427
15.0	0.751	0.430	0.570
17.5	0.824	0.294	0.706
20.0	0.896	0.16	0.833
22.5	0.969	0.048	0.952
25.0	1.000	0.000	1.000

Table 7-2
Containment Failure
Distributions for Expert B

Impulse (kPa-s)	Total Cumulative Failure Probability	Conditional Probabilities	
		Level 2 Failure	Level 3 Failure
2.5	0.005	1.000	0.000
5.0	0.118	1.000	0.000
7.5	0.285	1.000	0.000
10.0	0.474	1.000	0.000
12.5	0.626	0.747	0.253
15.0	0.766	0.459	0.541
17.5	0.841	0.000	1.000
20.0	0.907	0.000	1.000
22.5	0.941	0.000	1.000
25.0	0.961	0.000	1.000
27.5	0.974	0.000	1.000
30.0	0.988	0.000	1.000
32.5	1.000	0.000	1.000

Table 7-3
Containment or Drywell Failure
Distributions for Expert C

Impulse (kPa-s)	Total Cumulative Failure Probability	Conditional Probabilities	
		Level 2 Failure	Level 3 Failure
2.5	0.000	1.000	0.000
5.0	0.000	1.000	0.000
7.5	0.000	1.000	0.000
10.0	0.000	1.000	0.000
12.5	0.030	0.813	0.187
15.0	0.059	0.626	0.374
17.5	0.106	0.696	0.305
20.0	0.154	0.765	0.235
22.5	0.217	0.721	0.279
25.0	0.279	0.677	0.323
27.5	0.339	0.674	0.326
30.0	0.398	0.671	0.329
32.5	0.453	0.678	0.322
35.0	0.507	0.686	0.314
37.5	0.557	0.695	0.306
40.0	0.606	0.703	0.297
42.5	0.656	0.607	0.393
45.0	0.706	0.511	0.489
47.5	0.747	0.498	0.502
50.0	0.788	0.486	0.514
52.5	0.818	0.517	0.483
55.0	0.849	0.548	0.452
57.5	0.872	0.594	0.407
60.0	0.895	0.639	0.361
62.5	0.913	0.639	0.361
65.0	0.930	0.638	0.362
67.5	0.940	0.548	0.452
70.0	0.950	0.457	0.543
72.5	0.958	0.453	0.547
75.0	0.966	0.449	0.551
77.5	0.972	0.460	0.540
80.0	0.978	0.470	0.530
82.5	0.983	0.536	0.463
85.0	0.987	0.603	0.397
87.5	0.991	0.637	0.364
90.0	0.994	0.670	0.330

Table 7-3 (continued)

Impulse (kPa-s)	Total Cumulative Failure Probability	Conditional Probabilities	
		Level 2 Failure	Level 3 Failure
92.5	0.995	0.560	0.440
95.0	0.996	0.450	0.550
97.5	0.997	0.477	0.524
100.0	0.998	0.503	0.497
102.5	0.999	0.535	0.465

Table 7-4
Containment Failure
Aggregate Distributions

Impulse (kPa-s)	Total Cumulative Failure Probability	Conditional Probabilities	
		Level 2 Failure	Level 3 Failure
2.5	0.026	1.000	0.000
5.0	0.130	0.979	0.021
7.5	0.273	0.932	0.068
10.0	0.360	0.846	0.154
12.5	0.445	0.611	0.389
15.0	0.525	0.348	0.652
17.5	0.590	0.170	0.830
20.0	0.653	0.118	0.882
22.5	0.709	0.076	0.924
25.0	0.747	0.054	0.946
27.5	0.771	0.045	0.955
30.0	0.795	0.038	0.962
32.5	0.818	0.034	0.966
35.0	0.836	0.031	0.969
37.5	0.852	0.028	0.972
40.0	0.869	0.026	0.974
42.5	0.885	0.020	0.980
45.0	0.902	0.016	0.984
47.5	0.916	0.014	0.986
50.0	0.929	0.013	0.987
52.5	0.940	0.013	0.987
55.0	0.950	0.013	0.987
57.5	0.957	0.013	0.987
60.0	0.965	0.013	0.987

Table 7-4 (continued)

Impulse (kPa-s)	Total Cumulative Failure Probability	Conditional Probabilities	
		Level 2 Failure	Level 3 Failure
62.5	0.971	0.013	0.987
65.0	0.977	0.012	0.988
67.5	0.980	0.010	0.990
70.0	0.983	0.008	0.992
72.5	0.986	0.007	0.993
75.0	0.989	0.007	0.993
77.5	0.991	0.007	0.993
80.0	0.993	0.007	0.993
82.5	0.994	0.007	0.993
85.0	0.996	0.008	0.992
87.5	0.997	0.008	0.992
90.0	0.998	0.008	0.992
92.5	0.998	0.007	0.993
95.0	0.999	0.005	0.995
97.5	0.999	0.005	0.995
100.0	0.999	0.006	0.994
102.5	1.000	0.006	0.994

Table 7-5
Drywell Failure
Distributions for Expert A

Impulse (kPa-s)	Total Cumulative Failure Probability	Conditional Probabilities	
		Level 2 Failure	Level 3 Failure
5.0	0.036	0.979	0.021
7.5	0.076	0.951	0.049
10.0	0.129	0.907	0.093
12.5	0.180	0.877	0.123
15.0	0.245	0.849	0.151
17.5	0.324	0.821	0.179
20.0	0.404	0.793	0.207
22.5	0.446	0.778	0.222
25.0	0.474	0.767	0.233
27.5	0.502	0.757	0.243
30.0	0.530	0.747	0.253
32.5	0.558	0.737	0.263

Table 7-5 (continued)

Impulse (kPa-s)	Total Cumulative Failure Probability	Conditional Probabilities	
		Level 2 Failure	Level 3 Failure
35.0	0.583	0.725	0.275
37.5	0.595	0.707	0.293
40.0	0.607	0.688	0.312
42.5	0.620	0.670	0.330
45.0	0.632	0.651	0.349
47.5	0.645	0.633	0.367
50.0	0.657	0.615	0.385
52.5	0.669	0.596	0.404
55.0	0.682	0.578	0.422
57.5	0.694	0.559	0.441
60.0	0.707	0.541	0.459
62.5	0.719	0.523	0.477
65.0	0.731	0.504	0.496
67.5	0.744	0.486	0.514
70.0	0.756	0.466	0.534
72.5	0.769	0.446	0.554
75.0	0.781	0.425	0.575
77.5	0.793	0.404	0.596
80.0	0.806	0.383	0.617
82.5	0.818	0.363	0.637
85.0	0.831	0.342	0.658
87.5	0.843	0.321	0.679
90.0	0.856	0.301	0.699
92.5	0.868	0.280	0.720
95.0	0.880	0.259	0.741
97.5	0.893	0.238	0.762
100.0	0.905	0.218	0.782
102.5	0.918	0.197	0.803
105.0	0.930	0.176	0.824
107.5	0.942	0.156	0.844
110.0	0.947	0.142	0.858
112.5	0.952	0.129	0.871
115.0	0.957	0.115	0.885
117.5	0.962	0.101	0.899
120.0	0.968	0.087	0.913
122.5	0.973	0.073	0.927
125.0	0.978	0.059	0.941

Table 7-6
Drywell Failure
Distributions for Expert B

Impulse (kPa-s)	Total Cumulative Failure Probability	Conditional Probabilities Level 2 Failure	Conditional Probabilities Level 3 Failure
2.5	0.000	1.000	0.000
5.0	0.024	1.000	0.000
7.5	0.089	1.000	0.000
10.0	0.183	1.000	0.000
12.5	0.285	1.000	0.000
15.0	0.399	1.000	0.000
17.5	0.509	1.000	0.000
20.0	0.596	0.825	0.175
22.5	0.688	0.708	0.292
25.0	0.766	0.459	0.541
27.5	0.811	0.000	1.000
30.0	0.856	0.000	1.000
32.5	0.901	0.000	1.000
35.0	0.921	0.000	1.000
37.5	0.941	0.000	1.000
40.0	0.955	0.000	1.000
42.5	0.964	0.000	1.000
45.0	0.972	0.000	1.000
47.5	0.980	0.000	1.000
50.0	0.988	0.000	1.000
52.5	0.996	0.000	1.000
55.0	1.000	0.000	1.000

Table 7-7
Drywell Failure
Aggregate Distributions

Impulse (kPa-s)	Total Cumulative Failure Probability	Conditional Probabilities	
		Level 2 Failure	Level 3 Failure
2.5	0.000	1.000	0.000
5.0	0.020	0.993	0.007
7.5	0.055	0.984	0.016
10.0	0.104	0.969	0.031
12.5	0.165	0.897	0.103
15.0	0.234	0.825	0.175
17.5	0.313	0.839	0.161
20.0	0.385	0.794	0.206
22.5	0.450	0.736	0.264
25.0	0.506	0.634	0.366
27.5	0.551	0.477	0.523
30.0	0.595	0.473	0.527
32.5	0.637	0.472	0.528
35.0	0.670	0.470	0.530
37.5	0.698	0.467	0.533
40.0	0.723	0.464	0.536
42.5	0.746	0.426	0.574
45.0	0.770	0.387	0.613
47.5	0.790	0.377	0.623
50.0	0.811	0.367	0.633
52.5	0.828	0.371	0.629
55.0	0.844	0.375	0.625
57.5	0.855	0.384	0.616
60.0	0.867	0.393	0.607
62.5	0.877	0.387	0.613
65.0	0.887	0.381	0.619
67.5	0.895	0.344	0.656
70.0	0.902	0.308	0.692
72.5	0.909	0.300	0.700
75.0	0.916	0.291	0.709
77.5	0.922	0.288	0.712
80.0	0.928	0.284	0.716

Table 7-7 (continued)

Impulse (kPa-s)	Total Cumulative Failure Probability	Conditional Probabilities	
		Level 2 Failure	Level 3 Failure
82.5	0.934	0.300	0.700
85.0	0.939	0.315	0.685
87.5	0.945	0.319	0.681
90.0	0.950	0.324	0.676
92.5	0.954	0.280	0.720
95.0	0.959	0.236	0.764
97.5	0.963	0.238	0.762
100.0	0.968	0.240	0.760
102.5	0.972	0.244	0.756
105.0	0.976	0.248	0.752
107.5	0.980	0.280	0.720
110.0	0.982	0.313	0.687
112.5	0.984	0.319	0.681
115.0	0.986	0.325	0.675
117.5	0.987	0.268	0.732
120.0	0.989	0.210	0.790
122.5	0.991	0.210	0.790
125.0	0.993	0.209	0.791

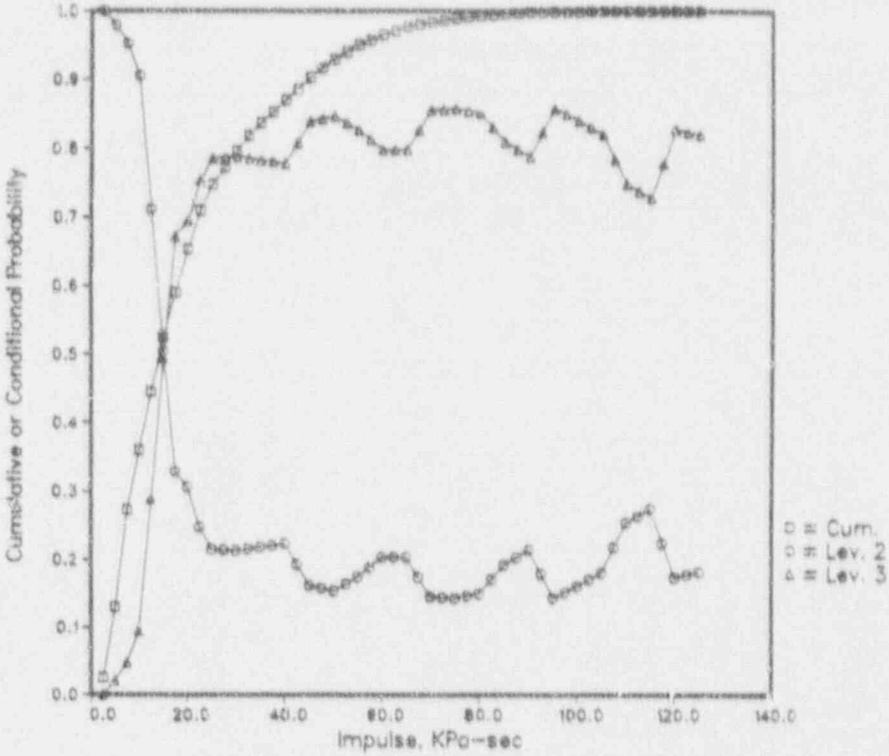

Figure 7-1. Aggregate Containment Failure Distributions.

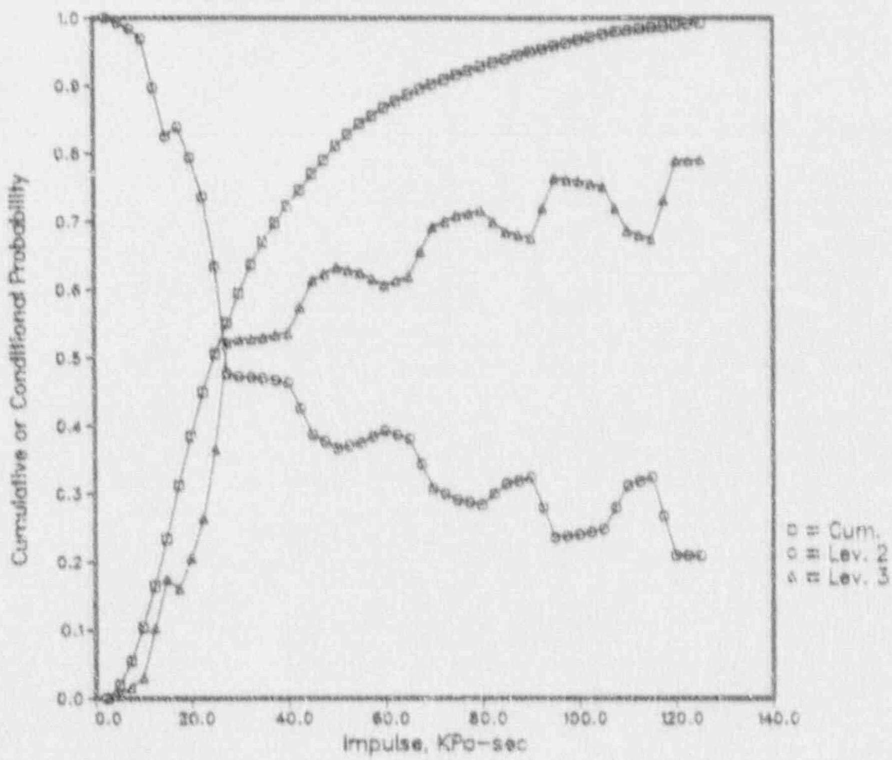

Figure 7-2. Aggregate Drywell Failure Distributions.

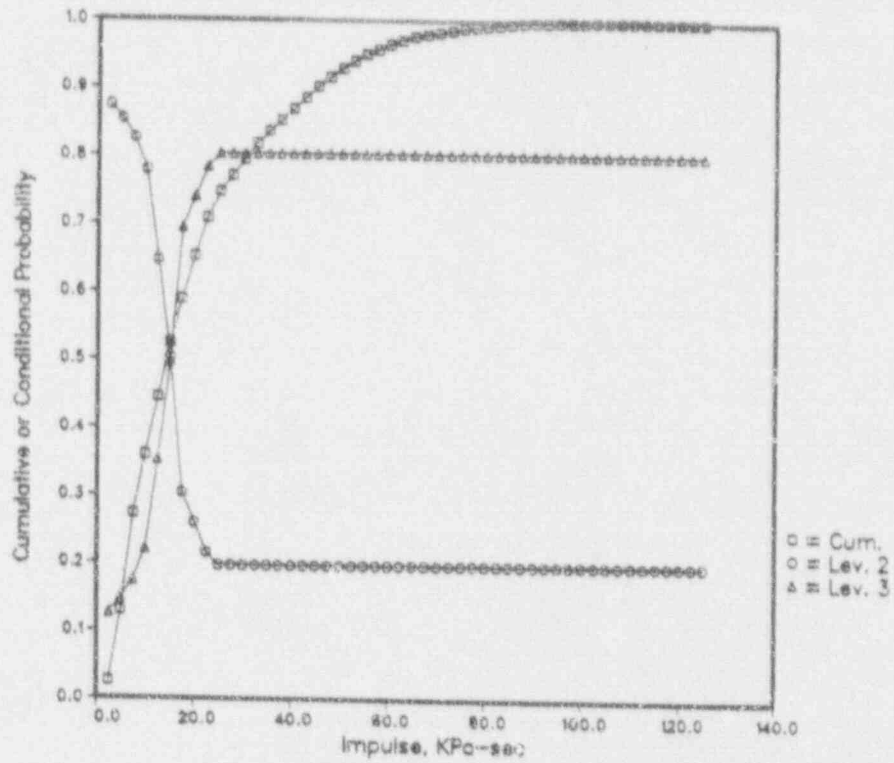

Figure 7-3. Aggregate Smoothed Containment Failure Distributions.

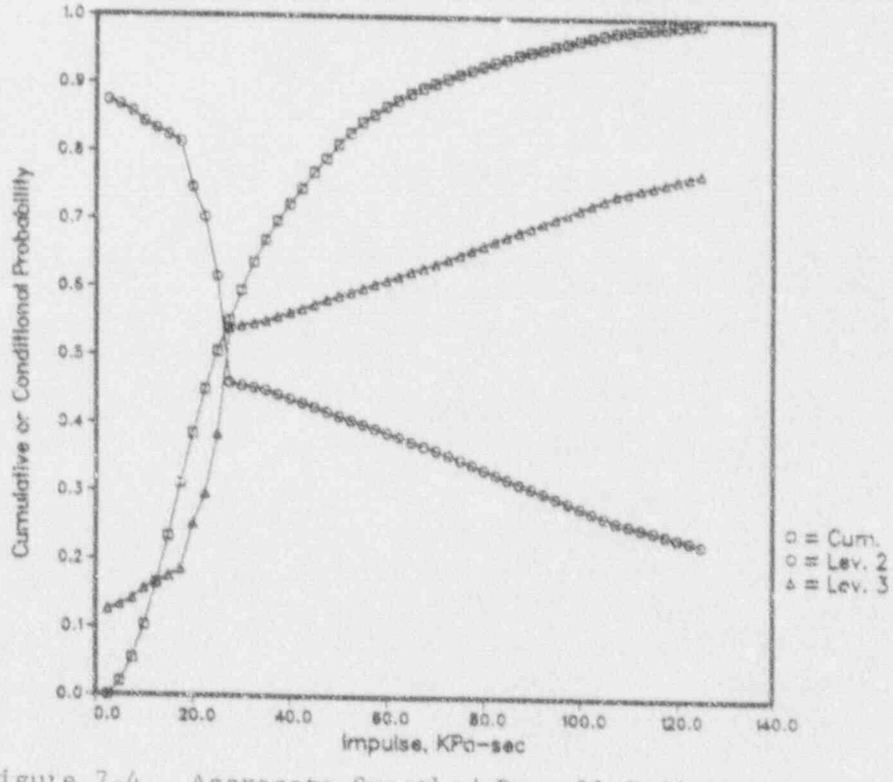

Figure 7-4. Aggregate Smoothed Drywell Failure Distributions.

Individual Elicitations for Issue 7

Expert A's Elicitation

Containment Failure Due to Wetwell Detonations at Grand Gulf

Description of Expert A's Rationale/Methodology

Expert A first considered the strength of the containment due to a static pressure. He estimated the wetwell failure pressure to be between 40 and 75 psig, with a median (based on reported yield strength) of 56 psig. For the structure between the drywell and the wetwell--which he considered to be more uncertain--he took low, median, and high values to be 30, 50, and 80 psig, respectively.

He then considered the response of the structure to pulses with durations of 1 to 15 ms, with low, median, and high values of containment strength, and high and low "pulse amplification factors" of 3 and 0.1. The lower value of the pulse amplification factor accounts for the fact that the impulse in the annular region between the wetwell and drywell could not possibly be axisymmetric, and therefore must be less severe than the axisymmetric case. For detonations above the drywell, the minimum pulse amplification factor was 0.5.

Expert A then computed the response of a single degree of freedom system, and calculated the impulse to give five times the yield deflection, corresponding to approximately 2% strain in the liner. Because of strain concentrations, 2% average strain would give much higher local strains, and would be expected to cause failure.

Expert A performed analyses for three cases: failure in containment above the drywell, due to detonation above the drywell (Case 1A); failure of the containment due to a detonation in the wetwell annulus (Case 1B), and failure of the drywell due to a detonation in the wetwell annulus (Case 1C).

The location of a detonation is uncertain. It is assumed that ignition sites are equally likely in the dome above the drywell and in the annulus between the drywell and the containment structure. For failure of the containment, therefore, the overall cumulative distribution function (CDF) is taken to be the average of the CDF for Cases 1a and 1b.

Case 1 was calculated in detail. Case 2 can be derived from Case 1 by multiplying impulse values by the factor $(1-P_s/P_y)$, where P_s is the static pressure, and P_y is the pressure to cause yield. For Case 3, the Expert believed that any damage to the drywell would be highly localized, and it would be unlikely that the damaged area would coincide with the area to which impulse was applied. Therefore, Case 3 is not distinct from Case 1.

Level 4 was ruled out for the drywell, because the load would be compressive, and the Expert did not believe this level of damage was possible for compressive loading.

Results of Expert A's Elicitation

Expert A provided impulses for five failure probabilities for Cases 1a, 1b, and 1c as shown in Tables A-1, A-2, and A-3. To extend these distributions to 0 and 1.0 probabilities, linear extrapolation was used. However, in no case was the 0th percentile impulse allowed to be less than half the 5th percentile impulse.

Table A-1
Case 1A--Failure of Containment Above Drywell, Due to Detonation Above Drywell

Side-On Impulse (psi-s)	Probability of Failure	Conditional Probability For Each Level		
		Level 1	Level 2	Level 3
0.04	0.05	0.95	0.05	0.00
0.5	0.25	0.50	0.50	0.00
0.75	0.50	0.25	0.70	0.05
1.00	0.75	0.10	0.80	0.10
2.00	0.95	0.00	0.50	0.50

Table A-2
Case 1B--Failure of Containment at Annulus, Due to Detonation in the Annulus

Side-On Impulse (psi-s)	Probability of Failure	Conditional Probability For Each Level		
		Level 1	Level 2	Level 3
0.4	0.05	0.95	0.05	0.00
2.0	0.25	0.50	0.40	0.10
3.0	0.50	0.10	0.60	0.30
5.0	0.75	0.00	0.50	0.50
10.0	0.95	0.00	0.20	0.80

Table A-3
Case 1C--Failure of Drywell/Wetwell Structure
Due to Detonation in Wetwell Annulus

Side-On Impulse (psi-s)	Probability of Failure	Conditional Probability For Each Level: Level 1	Level 2	Level 3	Level 4
0.4	0.05	0.90	0.10	0.00	0.00
1.0	0.25	0.60	0.40	0.00	0.00
1.5	0.50	0.20	0.75	0.05	0.00
3.0	0.75	0.05	0.85	0.10	0.00
10.0	0.95	0.00	0.75	0.25	0.00

To aggregate this Expert's distributions with those of the other experts', and to average his distributions for Cases 1A and 1B, it is necessary to develop independent CDFs for each failure level. The probability density function (PDF) is calculated from the CDF. The average density over an impulse level "i" is

D(i-1/2) = (P(i)-P(i-1))/(I(i)-I(i-1)),

where:

D(i-1/2) is the probability density at the midpoint of the interval i-1 to i;

P(i) is the probability of failure at interval i;

P(i-1) is the probability of failure at interval i-1;

I(i) is the impulse at interval i, and

I(i-1) is the impulse at interval i-1.

The probability of failure in level m within the interval is the density across the interval, times the average conditional probability of failure in level m for the interval:

D(i-1/2,m) = D(i-1/2) * [Pr(F(i,m:F) + Pr(F(i-1,m:F)] / 2,

where:

D(i-1/2,m) is the probability density of failure at the midpoint of the interval i-1 to i, in level m,

Pr(F(i,m:F) is the conditional probability of failure at level m, interval i, given that failure occurs at the interval.

The CDF for failure in level m (independent of failure at all other levels) is the integral of the density D(i,m) from the lowest to the highest level of impulse. The independent CDFs for each level are then averaged for Cases 1A and 1B. Also, the independent CDFs will be averaged with those of the other experts to give aggregated CDFs for failure at each level. The assumption of independence implies that the total failure probability is:

$$P_T = 1-(1-P_1)(1-P_2)(1-P_3),$$

where:

P_T is the total failure probability, that is, the probability of failure at any level;

P_1 is the probability of failure at Level 1, independent of all other levels;

P_2 is the probability of failure at Level 2, etc.

As a check on the calculations, the total probability of the independent CDFs for each level must be equal to the total probability given by the expert. Because the independent CDFs have been calculated using numerical differentiation and integration--with the inaccuracies to which these processes are subject--the averaged CDFs will not usually be exactly equal to the computed CDFs. A factor "k" was calculated, which, when multiplied by the density for each failure level, made the computed total CDF equal to the original CDF at each point.

The independent CDFs are given in Tables A-4 through A-6.

Table A-4
Case 1A: Independent CDFs for Each Failure Level

	Independent Failure Probabilities			
Side-On Impulse (psi-s)	Level 1	Level 2	Level 3	Total
0.02	0.000	0.000	0.000	0.00
0.04	0.049	0.001	0.000	0.05
0.5	0.202	0.060	0.000	0.25
0.75	0.324	0.254	0.008	0.50
1.0	0.397	0.568	0.039	0.75
2.0	0.422	0.893	0.190	0.95
2.25	0.422	1.000	0.509	1.00

Table A-5
Case 1B: Independent CDFs for Each Failure Level

Side-On Impulse (psi-s)	Independent Failure Probabilities Level 1	Level 2	Level 3	Total
0.2	0.000	0.000	0.000	0.00
0.4	0.049	0.001	0.000	0.05
2.0	0.203	0.049	0.011	0.25
3.0	0.305	0.219	0.079	0.50
5.0	0.329	0.487	0.273	0.75
10.0	0.329	0.729	0.724	0.95
11.25	0.329	0.760	1.000	1.00

Table A-6
Case 1C: Independent CDFs for Each Failure Level

Side-On Impulse (psi-s)	Independent Failure Probabilities Level 1	Level 2	Level 3	Total
0.25	0.000	0.000	0.000	0.00
0.4	0.048	0.003	0.000	0.05
1.0	0.206	0.055	0.000	0.25
1.5	0.335	0.241	0.008	0.50
3.0	0.388	0.575	0.039	0.75
10.0	0.398	0.906	0.119	0.95
11.75	0.398	1.000	0.168	1.00

The overall probability of containment failure is the average, by levels, of the independent probabilities for Cases 1a and 1b. Figure A-1 shows the averaged failure probabilities for Levels 1 through 3, along with the total cumulative failure probability. The ordinate on each curve is the probability that the impulse required to cause failure of that level (independent of all other levels) is no greater than the value of impulse on the abscissa. The ordinate for the "total" curve is the probability that the impulse required to cause failure at any level is no greater than the value on the abscissa.

Table A-1, for containment failure, is obtained from Tables A-4 and A-5 by eliminating Level 1, interpolating to obtain failure probabilities for 2.5 kPa-s, and combining independent distributions to obtian a total cumulative distribution and conditional probabilities for failure level. Table A-5, for drywell failure, is obtained analogously from Table A-6.

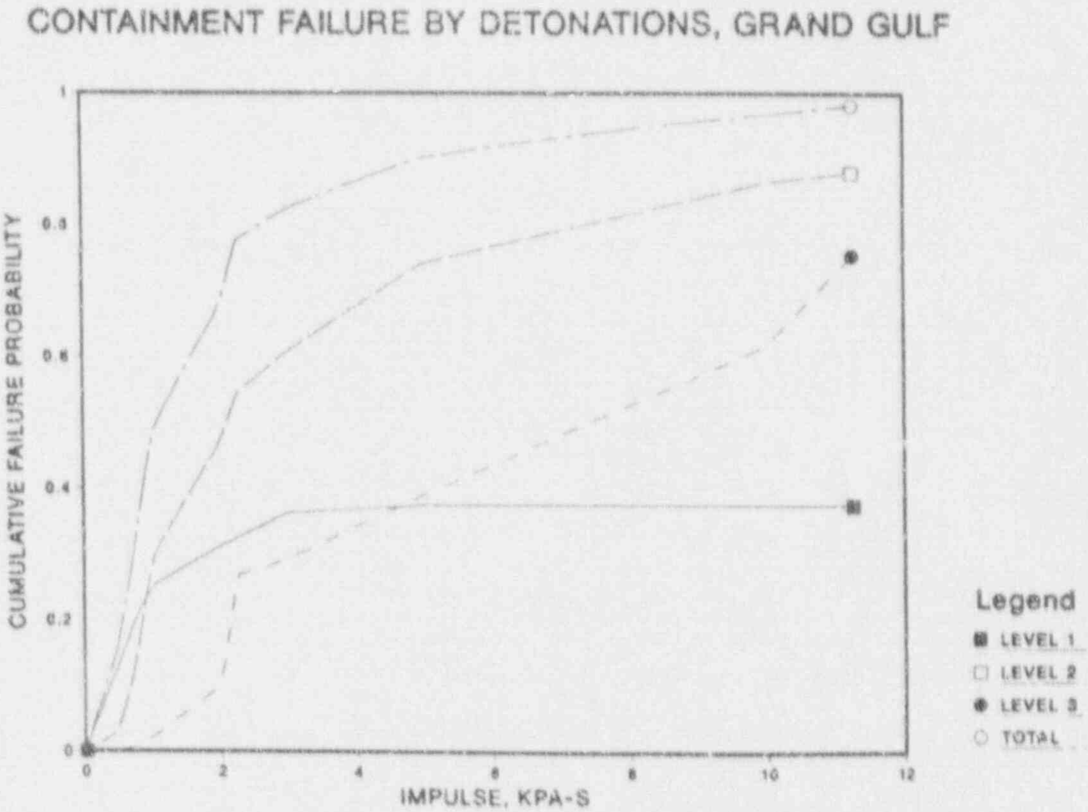

Figure A-1. Averaged Failure Probabilities for Levels 1 Through 3.

<u>Sources of Uncertainty</u>

A major source of uncertainty is the description of the detonation. If the initiation point, duration, and reflections of the impulse were accurately known, the structural response could be calculated with much less uncertainty. There is also considerable uncertainty with regard to the level of damage expected; however, this uncertainty is also less than the uncertainty in the initial conditions.

<u>Suggested Methods for Removing Uncertainty</u>

Because the major source of uncertainty is the stochastic nature of the initial conditions, it is virtually impossible to make marked reduction in the uncertainty.

Expert B's Elicitation

Containment Fa..ure Due to Wetwell Detonations at Grand Gulf

Description of Expert B's Rationale/Methodology

Expert B considered five basic failure modes: (1) failure of the drywell concrete, (2) failure of the drywell head, (3) failure of the drywell head closure pins, (4) failure of the vacuum breaker pipes, and (5) failure of any other pipe penetrations. He worked from existing containment analysis results, but he had no drywell analysis results or structural drawings. He estimated concrete strength of the drywell by the same safety factors used for the containment.

Expert B concluded that vacuum breaker failure was unlikely because the path that the pressure pulse must follow to the vacuum breakers is quite tortuous. For a detonation in the drywell, the momentum of the pulse would be absorbed in the two 90° elbows embedded in the concrete and one more 90° elbow in the piping. Although he had no detailed description of the valves, they are designed to withstand 35 psi pressure, so, in his opinion, failure from a detonation impulse is not likely. For a detonation in the upper part of the wetwell, approximately 10 ft of 8 in. Schedule 40 pipe and valves are exposed to the pressure pulse in the containment atmosphere. It would be more likely that a detonation would fail the vacuum pipes because of drag forces from the detonation than by a reflected wave. However, this is not a likely possibility. The pipe is expected to hinge near the slab and at a support. Large ductility can be mobilized (in his judgment, 10 to 20) before pipe fracture. Very high pressures can be tolerated, well outside the range of credible pressures.

The Expert concentrated on the drywell-wetwell wall. Leak and rupture appear to be controlled by the concrete. Simple hand calculations of the expected strain in the drywell liner were conducted by the expert to estimate the expected static capacity and to estimate the elastic frequency. The peak dynamic reflected pressures at which leak was expected to occur were translated to impulse by assuming impulse durations of 3 to 10 ms with varying shapes. He did include consideration of secondary impulses in calculating the impulse from peak dynamic pressure. He looked for places where the strain concentrates in the liner. Leakage could occur as well at other places but ductile failure there would lead to rupture. He used conservative assumptions to form a lower bound. Leak was expected from ductilities of about 3 to 8.

Expert B did not differentiate between probability of failure at Level 2 and Level 3, both of which he classified as leakage. Level 2 and Level 3 failures imply no rebar failure and no large hole in the concrete. An example of a Level 2 failure would be a tear in the liner and a crack in the concrete with a fraction of an inch width extending several feet in length. This type of failure would be expected to occur most often as a result of strain concentrations around penetrations etc. An example of a Level 3 failure would also consist of a tear in the liner and a narrow concrete crack, but this time extending over a much greater length. This type of failure would be expected to occur away from areas of strain concentration and would be expected to occur in the area of high average hoop strains. A crack of this type could be expected to run over half the height of the wall or more.

The Expert gave a separate distribution for rupture. Rupture pressures were estimated by assuming a ductile liner, no controlling strain concentrations and an average strain of 4 to 5%. In order for the concrete to rupture, the rebar would be required to fracture before liner rupture. Rupture pressures were estimated using the same pressure pulse assumptions (i.e., translating a reflected pressure into impulse by assuming a 3 to 10 ms pulse duration) but using higher liner ductilities of from about 5 to 15 to reach the expected reinforcing steel uniaxial strains required to cause failure.

Head failure was dismissed as a failure mode because there was no possibility of a detonable mixture there. If there is a possibility of getting detonable mixtures in the upper head of the drywell, he did make estimates of the pressures required to produce shear pin failure.

Expert B did not look at details such as hatches or electrical penetrations. He expressed concern that some hatches could be one-way hatches and could unseat if overpressures are encountered in the unexpected direction.

Expert B obtained his failure probability distributions for the containment (wetwell) by taking his distributions for the drywell and reducing the failure pressures down by 40%.

Finally, all the estimates were predicated on the assumption that the impulse duration of the detonation would range from 3 to 10 ms. Changing the pulse duration to 20 to 40 ms would require the Expert to take a closer look at the structure vibration modes, since the dynamic amplification is a non-linear effect once yield is exceeded.

Results of Expert B's Elicitation

Case 1

Table B-1 shows Expert B's estimate of the probability of leakage in the drywell due to concrete failure as a function of reflected pressure and impulse. At the lower values of reflected pressure he expects a Level 2 leak, at the higher values of reflected pressure he expects a Level 3 leak to result. The dividing line between Level 2 and Level 3 leaks is about 400 psig.

Table B-1
Drywell Leakage

Cumulative Failure Probability for Leakage	Reflected Pressure (psig)	Impulse to Dry Well (psig-s)	Impulse (kPa-s)
0.02	70	0.7	4.8
0.05	100	0.9	6.2
0.10	140	1.14	7.8
0.25	230	1.7	11.7
0.5	400	2.5	17.2
0.75	700	3.5	24.1
0.9	1200	4.7	32.4
0.95	1600	5.6	38.6
0.98	2300	6.9	47.6

Table B-2 depicts his estimate of the probabilities of rupture failure of the drywell. His rupture curve applies to Levels 3 and 4. Above a reflected pressure of 2000 psig a Level 4 leak would be more likely than a Level 3 leak. Below a reflected pressure of 1300 psig a Level 3 leak would be more likely than a Level 4 leak. There is no chance of a Level 4 leak at or below 800 psig.

Table B-2
Drywell Rupture

Cumulative Failure Probability for Rupture	Reflected Pressure (psig)	Impulse to Dry Well (psig-s)	Impulse to Drywell (kPa-s)
0.02	300	3.0	20.7
0.05	410	3.5	24.7
0.10	530	3.9	26.2
0.25	810	4.8	33.1
0.50	1300	6.0	41.4
0.75	2090	8.4	58.0
0.90	3200	11.4	78.7
0.95	4100	13.7	117.3
0.98	5600	17.0	132.5

In order to put these distributions into the required format for aggregation with the other experts' distributions it was necessary to separate the probabilities for the Levels 2, 3 and 4 failures and to extend the distributions to 0 and 1.0 probabilities. The results are shown in Table B-3. The impulse units have been converted to kPa-s in Table B-3.

Table B-3
Conditional probabilities of Drywell Failure

Cumulative Failure Probability	Impulse to Drywell(kPa-s)	Conditional Probability Level 2	Level 3	Level 4
0.00	3.91	1.0	0.0	0.0
0.02	4.83	1.0	0.0	0.0
0.05	6.21	1.0	0.0	0.0
0.10	7.86	1.0	0.0	0.0
0.25	11.72	1.0	0.0	0.0
0.50	17.24	1.0	0.0	0.0
0.54	18.40	1.0	0.0	0.0
0.62	20.69	0.75	0.25	0.0
0.75	24.13	0.67	0.33	0.0
0.80	26.89	0.0	1.00	0.0
0.90	32.41	0.0	1.0	0.0
0.95	38.61	0.0	0.85	0.15
[illegible]	41.37	0.0	0.67	0.33
0.98	47.58	0.0	0.56	0.44
1.00	53.60	0.0	0.45	0.55
1.00	57.92	0.0	0.33	0.67
1.00	78.60	0.0	0.15	0.85
1.00	94.46	0.0	0.05	0.95
1.00	117.21	0.0	0.02	0.98
1.00	132.40	0.0	0.0	1.00

Conditional probabilities for failure at each level were then converted to joint cumulative probabilities as shown in Table B-4.

Table B-4
Joint Cumulative Probability of Drywell Failure

Cumulative Failure Probability	Impulse to Drywell(kPa-s)	Joint Cumulative Probability Level 2	Level 3	Level 4
0.00	3.91	0.0	0.00	0.00
0.02	4.83	0.02	0.00	0.00
0.05	6.21	0.05	0.00	0.00
0.10	7.86	0.10	0.00	0.00
0.25	11.72	0.25	0.00	0.00
0.50	17.24	0.50	0.00	0.00

Table B-4 (continued)

Cumulative Failure Probability	Impulse to Drywell(kPa-s)	Joint Cumulative Probability Level 2	Level 3	Level 4
0.54	18.40	0.54	0.00	0.00
0.62	20.69	0.60	0.02	0.00
0.75	24.13	0.69	0.06	0.00
0.80	26.89	0.69	0.11	0.00
0.90	32.41	0.69	0.21	0.00
0.95	38.61	0.69	0.26	0.01
0.96	41.37	0.69	0.26	0.01
0.98	47.58	0.69	0.27	0.02
1.00	53.60	0.69	0.28	0.03
1.00	57.92	0.69	0.28	0.03
1.00	78.60	0.69	0.28	0.03
1.00	94.46	0.69	0.28	0.03
1.00	117.21	0.69	0.28	0.03
1.00	152.40	0.69	0.28	0.03

Linear interpolation is used to derive failure probabilities for the 2.5 kPa-s increments shown in Table 7-6 for the drywell. Levels 3 and 4 are combined and listed as Level 3 in Table 7-6. Table 7-2, for containment failure, is determined from Table 7-6 by multiplying the impulse levels by 0.60 as explained above.

Case 2

Case 2 can be derived from Case 1 by multiplying impulse values by the factor $(1-P_s/P_y)$, where P_s is the static pressure, and P_y is the pressure to cause yield.

Sources of Uncertainty

The main sources of uncertainty were the Expert's lack of knowledge of the material properties of the concrete and his lack of knowledge of the details of the plant, purely deterministic uncertainties. The assumption of a 3 to 10 ms pulse duration is also of major importance.

Suggested Methods for Reducing Uncertainty

The only additional, immediately available, information that would have helped the expert was detailed structural drawings, so that he could take a closer look at hatches and also verify the expected static pressure capacity. He had assumed the same factor of safety for the drywell as for the containment. Sandia analysts could check for the existence of one-directional hatches. If all the hatches in the drywell seat in both directions, then he thinks the hatches will not be a principal mode of failure.

Expert C's Elicitation

Containment Failure Due to Wetwell Detonations at Grand Gulf

Determination of Expert C's Rationale/Methodology

Case 1

Expert C considered a single detonation in the wetwell with no preconditioning. He assumed the detonation resulted in an axisymmetric impulsive load to structure. He looked at two locations in the containment: the upper containment (dome region) and the annular space in the wetwell. The Expert felt the asymmetrical geometry of the wetwell would have a higher capacity than the dome region. The areas he reviewed were the containment dome, drywell dome, cylindrical shell at the spring line, containment and drywell personnel locks, containment equipment hatch, vacuum breakers, and the piping system. Expert C ruled out the containment dome because the cylindrical shell is weaker than the dome. He expected that the piping system would see a drag load rather than an impulse load. Because the drag load would be less than the impulse load, he ruled out failure of the piping system. The vacuum breakers would fail only if a detonation occurred right next to them and even if they did fail, the impulse would collapse the pipe and close off any leakage. It was the Expert's opinion that the areas of concern were the containment and drywell personnel locks, equipment hatch, and the shell at the spring line. However, it was hard for the Expert to believe that both doors would fail on the personnel lock.

The Expert assumed the leakage level could be related to the ductility ratio. Next, he looked at the range of static capacities and ductility ratios for the various areas of concern. From this information, the Expert assessed the failure probability of the containment and the drywell. He felt the same distribution would apply to both the containment and the drywell because they had similar failure modes.

The Expert defined three levels of leakage: very small leak, small leak, and large leak. The very small leak corresponds to roughly the nominal leakage level. The large leakage level corresponds to a leak that is greater than 1 ft^2, and this includes both Levels 3 and 4 when applied to the drywell.

Case 2

The failure probabilities for this case can be derived from Case 1 by multiplying impulse values by the interaction factor, $(1 - P_s/P_y)$, where P_s is the static pressure and P_y is the yield pressure.

Results of Expert C's Elicitation

For Case 1, the failure probabilities for a very small leak, a small leak, and a large leak are presented in Tables C-1, C-2, and C-3, respectively. The distributions tabulated in Tables C-1, C-2, and C-3 applied to both the containment structure and the structure between the wetwell and the drywell. Linear interpolation is used to generate failure probabilities for 2.5 kPa-s steps as shown in Table 7-3. Leakage Level 3 was eliminated as not being of interest. The Case 1 distributions may be used with an interaction equation to obtain the distributions for Case 2. Case 3 has been combined with Case 1.

Table C-1
Containment/Drywell Failure Probabilities
Very Small Leakage (Level 1)

Normal Impulse (psi-s)	Cumulative Probability
1.5	0.00
4.5	0.50
9.0	0.95

Table C-2
Containment/Drywell Failure Probabilities
Small Leakage (Level 2)

Normal Impulse (psi-s)	Cumulative Probability
1.5	0.00
3.0	0.15
6.0	0.50
12.0	0.95

Table C-3
Containment/Drywell Failure Probabilities
Large Leakage (Level 3)

Normal Impulse (psi-s)	Cumulative Probability
1.5	0.00
3.0	0.05
7.5	0.50
15.0	0.95

Sources of Uncertainty

The major sources of uncertainty were the location of the detonation, the characteristics of the dynamic load, and the material properties.

5.8. Issue 8. Pedestal Failure at Grand Gulf

Experts consulted: Subir Sen, Bechtel Corp., Richard Toland, United Engineers and Contractors; Walter von Riesemann, Sandia National Laboratories.

Issue Description

What distributions characterize the quantity of concrete erosion that will result in structural failure of the vessel pedestal at Grand Gulf? Structural failure of the vessel pedestal is defined to mean loss of support of the vessel such that gross motion of the vessel results. It was previously assumed that such failure will induce suppression pool bypass leakage from the drywell to the containment (wetwell).

The Structural Response Expert Panel felt that this assumption was wrong. They felt that there was a small likelihood that the failure of the pedestal would result in failure of the drywell structure and subsequent bypass. The probability of drywell failure, given pedestal failure, was elicited informally from this Panel.

Nine cases were outlined. They correspond to the different vertical erosion values, radial erosion values, and effective debris depths shown in Table 8-1.

Table 8-1
Issue Case Structure

Cases	Debris Depth (ft)	Radial Erosion Range (ft)	Vertical Erosion Depth (ft)
1	4	0 to 10	1.5
2	4	0 to 10	3.5
3	4	0 to 10	5.0
4	7	0 to 10	1.5
5	7	0 to 10	3.5
6	7	0 to 10	5.0
7	10	0 to 10	1.5
8	10	0 to 10	3.5
9	10	0 to 10	5.0

Summary of Results

Expert A felt that the pedestal failure depended on the radial erosion depth, not the axial erosion depth. He felt that the strength of the pedestal wall would depend on temperature and that at 900°F the wall would be relatively strong, but at 1600°F, the wall would have lost almost all strength. The expert felt that at high temperatures, the pedestal wall would crack and he postulated a behavior similar to conc[illegible] beams with rebar. He felt that there was a lower probability of pedestal failure for erosion belo[illegible] he drywell floor than for erosion above the drywell floor.

The NUREG-1150 analysts only used the information given in the curve appropriate for a 4-ft debris depth. The Molten Core Containment Interaction (MCCI) group felt that the concrete above that level was not in jeopardy.

A cumulative distribution was created directly from the curve provided in the elicitation notes. The distribution was inverted to give the probability of pedestal failure for different radial erosion depths--this was done for ease in combining this information with that given by the MCCI group.

Expert B assumed that the probability of pedestal failure depends only on radial erosion and the temperature of the rebar. While estimating failure probabilities, the expert felt that the outer vertical cage of rebar was the load element and discounted the concrete. This expert gave all of his results in terms of temperature of the outer rebar group. He stated that failure will occur in the range of 1200 to 1400°F. Because the Molten Core/Containment Interaction Expert Panel unanimously stated that the thermal front precedes the erosion front by only a few centimeters, the NUREG-1150 staff assigned a probability of 0.0 to pedestal failure until the erosion front reached the outer rebar group, at which point a probability of 1.0 was assigned.

Expert C based his analysis on a number of drawings of the pedestal region and observed that the pedestal contained a large amount of rebar. He performed a literature search to determine the effects of temperature on the mechanical properties of both the reinforcing steel and the concrete. He found that in the 1000 to 1500°F range, the reinforcing steel has a dramatic loss of ultimate strength, yield strength and modulus of elasticity. At 1000°, the compressive strength of concrete is 30 to 80% of its strength at room temperature. At 1600°F, the compressive strength is nearly zero. Expert C felt that if the inside steel loses its strength, the likelihood of pedestal failure is high.

He felt that the greater the vertical erosion, the less radial erosion is required to cause pedestal failure. He gave probabilities of pedestal failure dependent on radial erosion depths for three different vertical erosion depth cases (5 ft, 3.5 ft, and 1.5 ft.) The radial and axial erosion profile described by the expert's 5-ft vertical erosion depth case is unrealistic according to the Molten Core Containment Interaction Expert Panel. The probabilities for the 5 ft vertical erosion case were therefore neglected.

Because the probabilities of pedestal failure for the 3.5 and the 1.5 vertical erosion cases did not differ by a substantial amount, the two vertical erosion cases were averaged to simplify the aggregation with the other experts. The probabilities were averaged with the other experts dependent on radial erosion depth only.

Expert C assigned a low probability to drywell failure conditional on pedestal failure. He felt that there was a high probability that the pipes supporting the vessel would fail at one of the several large angle bends between the vessel and the drywell. This would preclude failure at a drywell penetration.

The summary of the expert results and the aggregated distribution is presented in Table 8-2.

Table 8-2
Experts' Results and Aggregated Distribution

	Probability of Pedestal Failure vs. Radial Erosion Depth											
Experts	0 ft	1.0 ft	2.5 ft	3.0 ft	3.3 ft	3.5 ft	3.7 ft	4.0 ft	4.4 ft	4.8 ft	5.5 ft	7 ft
A	0	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
B	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1	1
C	0	0.272	0.926	0.992	0.993	0.994	0.995	0.996	0.997	0.999	1	1

Arithmetic Average of Experts' Elicitations

Probability of Pedestal Failure vs. Radial Erosion Depth										
1 ft	2.5 ft	3 ft	3.3 ft	3.5 ft	3.7 ft	4 ft	4.4 ft	4.8 ft	5.5 ft	7 ft
0.090666	0.342	0.397333	0.431	0.464666	0.498333	0.532	0.565666	0.599666	0.966666	1

Only two experts provided informal information on the drywell failure following pedestal failure. Expert A estimated that the failure would occur with a probability of 0.25 and Expert C estimated that the failure would occur with a probability of 0.1. These were averaged to get an aggregated probability of 0.175.

Individual Elicitations for Issue 8

Expert A's Elicitation

Pedestal Failure at Grand Gulf

Determination of Expert A's Rationale/Methodology

The dependency of vertical erosion on pedestal failure was dropped by the Expert. The vertical erosion is into the base mat and, therefore, the Expert felt it would not affect the pedestal wall. In addition, the "effective" debris depths of 7 and 10 ft were combined into a debris depth that represents erosion above the drywell floor. The 4-ft debris depth represents erosion below the drywell floor. The Expert felt that the total amount of material eroded was not the primary factor but, rather, the depth and the location of the radial erosion (i.e., above or below the drywell floor). Thus, even though more material is eroded with an "effective" debris depth of 10 ft when compared to 7 ft, it is the radial erosion depth that will determine if the pedestal will fail or not and, therefore, these two locations can be combined to represent an above drywell floor depth.

For the load on the pedestal the Expert included the reactor pressure vessel (RPV) (without debris material) and the shield wall. He felt the load was relatively "light" compared to virgin support strength of the pedestal and, therefore, felt the strength of the pedestal wall would depend on its temperature. The Expert assumed that at 900°F the wall would still have good strength, but at 1600°F the wall would have lost nearly all of its strength. He assumed that the temperature gradient through the pedestal wall was linear and that at the erosion front the temperature was 1600°F while at the outside surface of the pedestal wall the temperature was 200°F. The Expert thought the high temperatures in the pedestal would crack the pedestal wall and, thus, he considered the wall as a bunch of concrete beams with rebar.

For erosion depths above the drywell floor (7 or 10 ft), the load from the RPV and the shield wall was compared against the reduced concrete section. With a 3-ft radial erosion depth the reduced section capacity is approximately equal to the load. With a 4-ft radial erosion depth the section capacity was significantly less than the load. With a 5-ft radial erosion depth, the Expert thought there was a 5% probability that the RPV piping would support the RPV. He felt the highly uncertain area was between radial erosion depths of 3 and 4 ft.

The Expert stated that there was a lower probability of pedestal failure for erosion below the drywell floor than for erosion above the drywell floor. He felt the section of the pedestal below the drywell floor was in a better configuration structurally to survive radial erosion. The large heat sink at this location will also reduce the probability of failure.

Results of Expert A's Elicitation

Expert A's probabilities for pedestal failure as a function of radial erosion depth for erosion above and below the drywell floor are presented in Table A-1.

Table A-1
Probability of Pedestal Failure

Radial Erosion Depth (ft)	Cumulative Probability Above Drywell Floor	Cumulative Probability Below Drywell Floor
1	0.00	0.00
2	0.15	0.05
3	0.40	0.25
4	0.75	0.60
5	0.95	0.85
6	1.00	0.95
7	1.00	1.00

The Expert stated that pedestal failure does not necessarily cause drywell leakage. The Expert felt that the conditional probability of drywell leakage given pedestal failure was definitely less than 50%. Not having analyzed the situation, the Expert suggested a 0.25 probability of drywell failure conditional on pedestal failure.

Sources of Uncertainty

The major sources of uncertainty in this issue were the temperature profile and history through the pedestal wall and the actual strength of the pedestal wall as a function of temperature.

Correlations with Other Variables

No correlations were discussed between other variables in the event trees and the variables discussed as part of this issue.

Expert B's Elicitation

Pedestal Failure at Grand Gulf

Determination of Expert B's Rationale/Methodology

The Expert grouped all the cases together. The Expert assumed that the probability of pedestal failure depends only on radial erosion and the temperature of the rebar, since the material strength of the pedestal is strongly dependent on temperature at temperatures above 800°F for steel and 300 to 400°F for concrete.

The pedestal is heavily reinforced with rebar. Rebar cages have been imbedded in the concrete close to each vertical face. In estimating failure probabilities the Expert considered the outer vertical cage of rebar as the load element and discounted the concrete. He looked at the yield strength (F_y) vs. temperature (T) and performed his calculations on an equivalent steel cylinder. The size of the equivalent cylinder was calculated as follows. The cage near the outer circumference of the pedestal consists of two rows of #11 rebar. The rebar is spaced every 4 in. There is thus about 9 in.^{2} cross-sectional area of rebar for every foot of pedestal outer circumference. The outer circumference of the pedestal is about 100 ft, giving a total of 900 in.^{2} of reinforcing steel.

The load on the steel is about 1800 k (1 k = 1 kipp = 1000 pounds) for the reactor pressure vessel, 200 k for the residual core (50%), 1500 k for the pedestal and 1.5×10^3 k for the shield wall. The total weight that must be supported is 5000 k.

The reduction in yield strength of #11 rebar as a function of temperature is given in Table B-1.

Table B-1
Reduction in Yield Strength vs. T(°F)

Temperature	800°	1000°	1200°	1400°
Fraction reduced	0.7	0.6	0.3	0.1

(Fraction of room temperature yield strength reduced)

The required strength of the rebar is 5000/900 = 5.6 ksi (kipps per square inch). At room temperature the yield strength of #11 rebar is 60 ksi. The reduction in yield strength that must take place before the pedestal fails is 5.6/60 = 0.1. An estimate of the buckling stress of an individual rebar, assuming no effective lateral support by concrete on a 5 ft length, is 8 ksi at 1200°F. Thus the temperature at which failure occurs is estimated to be in the range of 1200 to 1400°F.

Results of Expert B's Elicitation

The probability of pedestal failure is given as a function of average temperature in the rebar in Table B-2.

Table B-2
Probability of Pedestal Failure vs.
Average Temperature in the Outer Rebar Group

Cumulative Probability	Temperature (°F)
0.05	1200
0.50	1300
0.95	1400

The average temperature should be calculated at the elevation that gives the maximum temperature.

If the Expert is mistaken about the type of rebar used (# 1), the project can recalculate his probability distribution by recalculating the 0.5 probability point of the F_y vs T curve. One should just translate the curve described in Table B-2 so that the temperature at which the yield strength reaches 0.1 corresponds to the probability of 0.5 and the temperature at which the yield strength is 0.2 corresponds to 0.05. Given those two points, one should then construct a unimodal and symmetrical curve.

Sources of Uncertainty

The type of steel used for the rebar was not known for sure. The Expert assumed that the steel in the rebar was #11. Other sources of uncertainty are the Expert's knowledge of the dependence of material properties on temperature.

Correlations with Other Variables

Correlations with variables other than rebar temperature were not identified.

Suggested Methods for Reducing Uncertainty

This issue is more sensitive to concrete erosion rate than to structural parameters.

Expert C's Elicitation

Pedestal Failure at Grand Gulf

Description of Expert C's Rationale/Methodology

Expert C based his analysis on a number of drawings of the pedestal region. Figure C-1 is the sketch that accompanied the issue paper. Since it is not to scale, Expert C found it misleading. Figure C-2 (Reference C-1) and Drawing C-1048A (Reference C-2) give a better idea of the size and shape of the pedestal. Drawing C-1067C (Reference C-3) shows the rebar placement in the haunch area at the top of the pedestal, and Drawing C1070A (Reference C-4) show the placement of the door and the four openings at the top of the pedestal for the control rod drives (CRD) lines. There are two sumps in the cavity floor, as shown in Drawing C-1042 (Reference C-5).

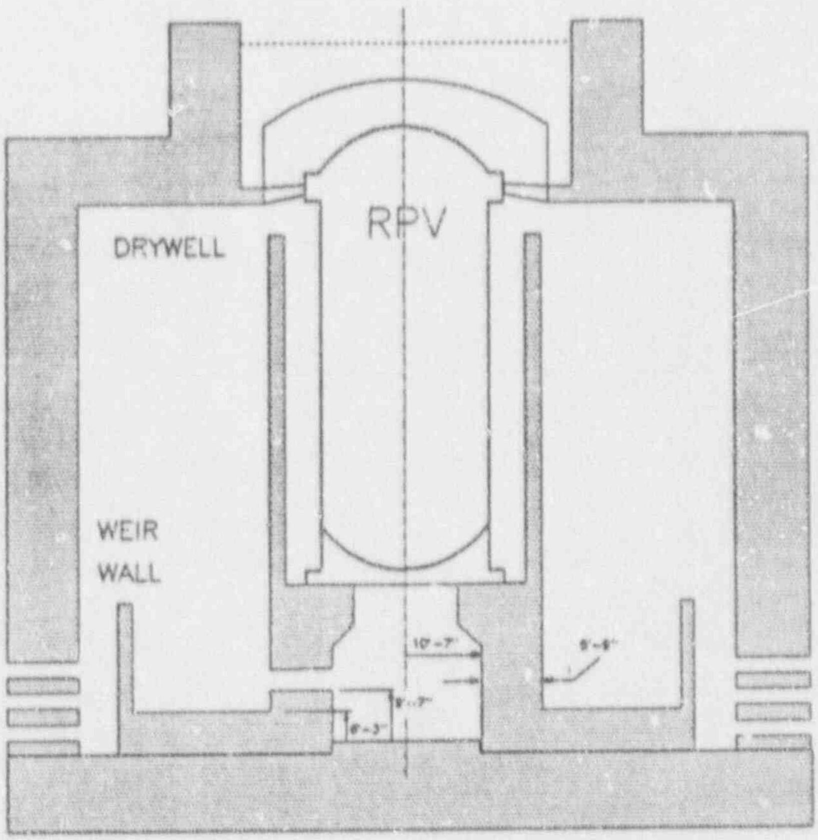

Figure C-1. Grand Gulf Reactor Pedestal Configuration.

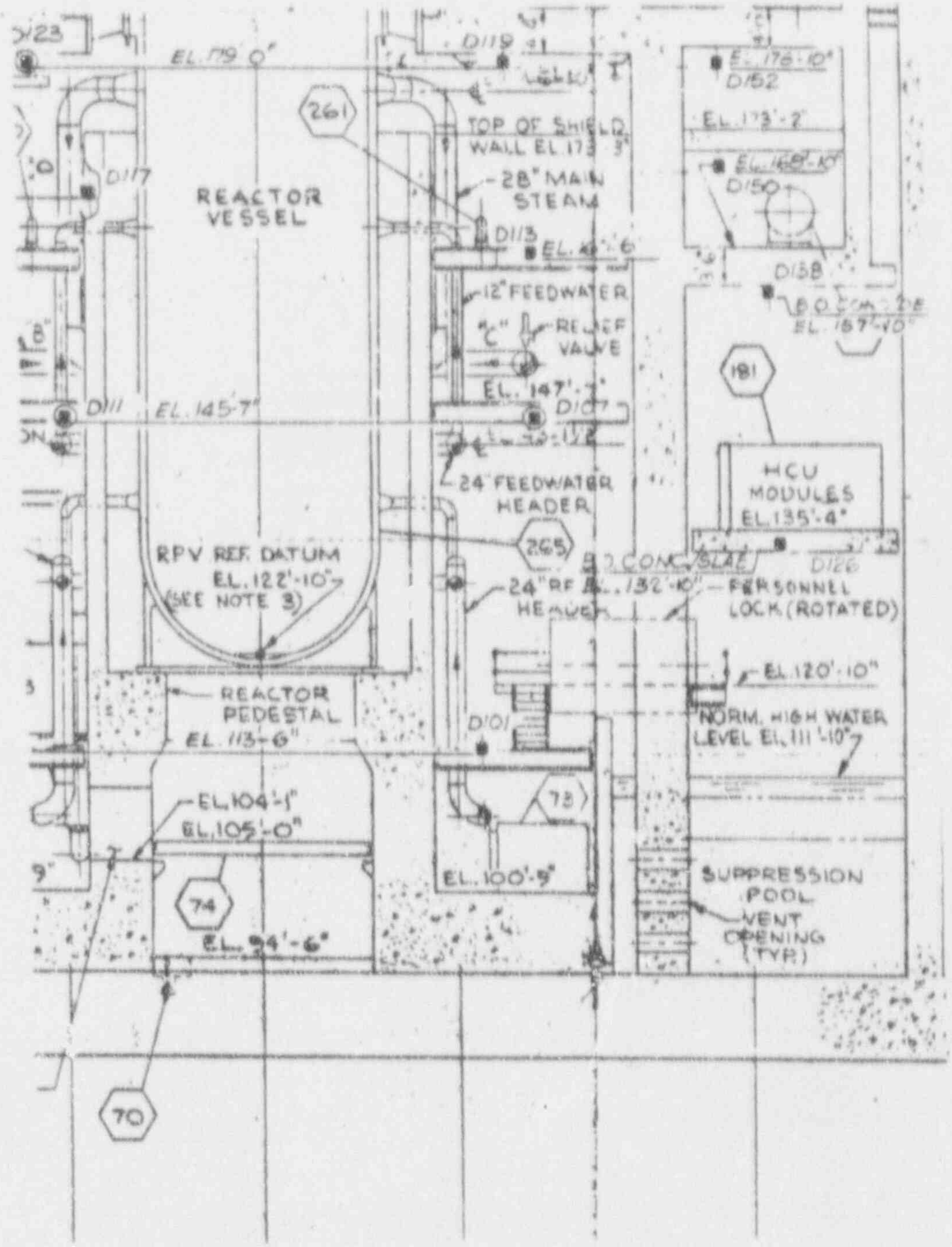

Figure C-2. Drawing C-1048A.

Expert C noted that the pedestal contained a large amount of rebar. In addition, there is a ring girder in Drawing 1067C (Reference C-3) (top elevation = 121 ft 4.5 in.) to which the RPV skirt flange is bolted. This ring girder is anchored to the pedestal by 3/5 in.-diameter bolts, some of which are 11 ft 8 in. long. In fact, the pedestal from approximately elevation 114 ft 0 in. to 119 ft 10 in. consists of a large amount of steel with a "little" concrete in between.

Expert C noted that the heavy reinforcing which extends all the way through the wall in the haunch region at the top of the pedestal in Drawing C-1067C (Reference C-3) does not extend below about elevation 114 ft (Reference C-2). From elevation 114 ft 0 in. down to elevation 100 ft 9 in. there is reinforcing steel only in the faces of the pedestal. From elevation 100 ft 9 in. down to elevation 93 ft 0 in. this steel is joined by the horizontal steel of the floor. This portion of the pedestal is thus heavily reinforced (see Reference C-2). The steel in the pedestal is #11 bars. In the vertical direction (i.e., horizontal steel) there are two bars every 9 in. in each face. There are two vertical bars every 4" in each face, except for one set of bars which are spaced at 8" as shown in Reference C-2.

There are five cutouts in the pedestal wall (see Drawing C-1070A, Reference C-4). The four CRD line openings have their bottoms at elevation 114 ft 0 in. This area is lined with steel and there is a steel frame which spans over the openings. The concrete around these openings appears to be heavily reinforced. The fifth opening is a door 3 ft wide and 7 ft high at azimuth 220°. The bottom of the opening is at 104 ft 1 in. The opening for the door is not steel-lined and the concrete around it does not appear to be reinforced.

There are two sumps in the cavity floor, as shown in Drawing C-1042 (Reference C-5). Their bottom elevation is 91 ft 6 in. and they are lined with 0.25 in.-steel plate. In fact, the entire cavity is lined with steel plate.

<u>Material Properties</u>. Since the loading condition involves elevated temperatures, a literature search was conducted to determine the effects of temperature on the mechanical properties of both the reinforcing steel and the concrete.

The ASME code for steels is divided into two classes. For light water reactors, the temperatures are assumed to be less than 900°F. The other class covers breeder reactor applications where higher temperatures are expected for selected components. Actual mechanical strength values for temperature above 800°F are difficult to obtain, but in the 1000 to 1500°F temperature range the reinforcing steel has a dramatic loss of ultimate strength, yield strength, and modulus of elasticity.

(References C-6 and C-7 were consulted. For A-514 and A-517 steel, curves are given for properties at elevated temperatures. At 1000°F, the ultimate and yield strengths are approximately 50% to 70% of their room temperature values. At 1200°F, the ultimate and yield strengths are approximately 30% of their room temperature values. At 1600°F, the ultimate and yield strengths are close to zero. While these steels have a different carbon content than the rebar steel, Expert C expected that the material properties of the rebar would show similar degradation with elevated temperature.)

The structural properties of concrete also decrease with increasing temperature. At 1000°F, the compressive strength of concrete is 30% to 80% of its strength at room temperature. At 1600°F, concrete's compressive strength is nearly zero. See References C-8 through C-12 for details.

Loading Parameters. The question being addressed is the failure of the Grand Gulf reactor pedestal due to erosion of the concrete by the molten core. The following items were given as input:

1. The thermal front is only slightly ahead of the erosion front;

2. Radial erosion up to 10 ft is to be considered;

3. The core debris will not fill the cavity above elevation 100 ft 9 in.;

4. Erosion depths of 1.5 ft, 3.5 ft and 5.0 ft are to be considered.

Expert C assumed that the erosion depth is measured from elevation 94 ft 6 in. He also ignored the equipment drain sump.

Rationale for Evaluation. Expert C concluded that there were too many uncertainties involved to attempt a structural analysis considering the rebar, concrete, and transformed areas. Rather, he examined the behavior of the pedestal considering only how the loads from the RPV are transmitted to the foundation.

The pedestal from elevation 100 ft 9 in. to elevation 114 ft 0 in. carries both the axial compression load and the bending load (the RPV load is eccentric) through the concrete, the vertical steel, and the hoop steel. Expert C assumed that if the inside steel (approximate radius 11 ft) has lost its strength, the likelihood of failure is high. At the same time (temperature) that the steel loses its strength, the concrete also loses its compressive strength. (The inside steel varies in radius from 10 ft 10 in. to 11 ft 3.5 in.)

The basemat (elevation 93 ft 0 in. to 100 ft 9 in.) contains radial steel and ring steel. Since the core debris will not be above 100 ft 9 in., and the thermal and erosion fronts will be close together, this steel will also have to be degraded to affect the load capacity of the pedestal.

The Expert considered loading on the drywell wall following pedestal failure from the main steam lines and the feedwater lines only. The remainder of the lines connecting the Reactor Pressure Vessel (RPV) to the drywell wall were not considered stout enough to put any substantial loads on the drywell wall.

The steam lines (28 in. diameter) leave the RPV at elevation 176 ft 10 in. and go through the drywell wall at elevation 151 ft 0 in. The feedwater lines (24 in. diameter) enter the RPV at elevation 164 ft and go through the drywell wall at 143 ft. There are at least two right angle turns and a considerable length of pipe between the RPV and the drywell wall in both the feedwater and steam lines. A high degree of flexibility is therefore expected in the piping. The Expert felt that both lines will either bend (distort) enough or fail within the drywell and not cause failure of the drywell wall. (He felt the distortion was more likely than failure.)

The Expert pointed out that two other points must be considered: (1) if the RPV does not fall straight down into the cavity, there could be side loads near elevation 185 ft that could fail the drywell head or the drywell wall; (2) the through guard pipe assembly bellows can fail due to either excessive motion or high internal pressure. The latter was felt to be unlikely since pressure will bleed through the suppression pool. The Expert felt that there would not be excessive deformation.

After pedestal failure, loads placed on the drywell wall by the main steam lines and the feedwater lines may lead to failure of this wall, which would result in suppression pool bypass. The failure could occur near elevation 185 ft from the side loads or as a bellows failure. Expert C concluded that suppression pool bypass by this means was unlikely; he assigned a probability of 0.1 for suppression pool bypass following pedestal failure.

Results of Expert C's Elicitation

The issue paper requested that each expert provide a curve giving the cumulative probability of pedestal failure for 1.5 ft 3.5 ft and 5.0 ft of vertical erosion. Curves illustrating the type of information desired were provided in Figure C-3 of the issue description. Expert C drew the curves reflecting his conclusions on a copy, which is included here as Figure C-3. Because this curve is hard to read, the 0%, 50%, 99%, and 100% points are listed below. The table gives radial erosion distances in feet.

Radial Erosion (ft) that Results in Pedestal Failure, for Vertical Erosion = Z

Cumulative Probability	Z = 5.0'	Z = 3.5'	Z = 1.5'
0%	0.25	0.25	0.25
50%	0.80	1.25	2.0
99%	1.5	2.25	3.0
100%	5.0	5.0	5.0

For an upper bound, Expert C assumed that if the radial erosion was 5 ft 0 in., the failure of the pedestal was assured, regardless of the vertical erosion. With 5 ft of radial erosion, only the outermost 9 in. of concrete and part of the outer layer of rebar is intact. Pedestal failure is certain at this point. For a lower bound, he reasoned that with only 0.25 ft (3 in.) of erosion, the inner layer of rebar is essentially intact and pedestal failure is not credible.

For 1.5-ft vertical erosion, Expert C concluded that there is a 50% probability of failure if the vertical erosion is 2.0 ft. Vertical erosion of 1.5 ft removes the concrete wearing course on top of the foundation mat.

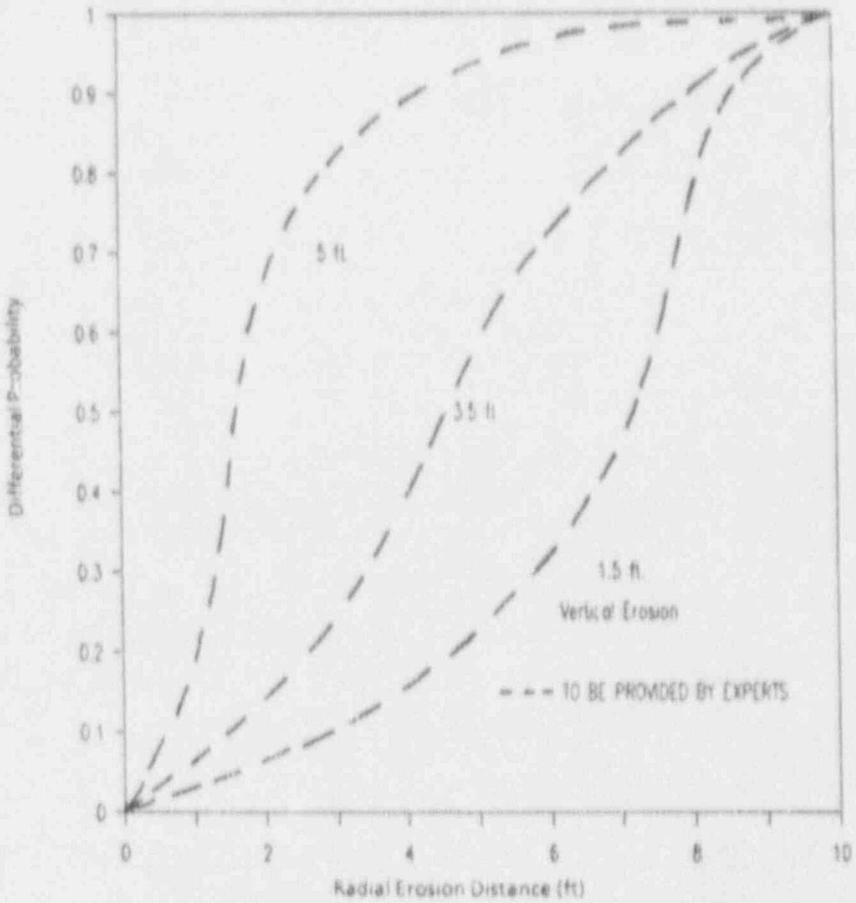

Figure C-3. Probability of Pedestal Failure.

The greater the vertical erosion, the less radial erosion is required to cause pedestal failure. Thus Expert C's midpoint values for 3.5 ft and 5.0 ft vertical erosion are less than for 1.5 ft vertical erosion. For 3.5 ft vertical erosion, he selected a midpoint value of 1.25 ft. For 5 ft of vertical concrete erosion, Expert C concluded that there would be a 50% chance of pedestal failure when the radial erosion was 0.8 ft (9.6 in.). The rebar along the inner surface of the wall lies between 3 in. and 12 in. inside the inner surface of the concrete. When the bulk of the rebar is gone, and 5 ft of the cavity floor is eroded away, Expert C felt the strength remaining would be marginal in resisting the forces tending to move the top of the pedestal inward around the 230° location.

<u>Sources of Uncertainty</u>

The major area of uncertainty is in calculating the strength of the footing (elevation 9_ ft 0 in. to elevation 100 ft 9 in. for the pedestal. Any material behind the erosion front has no strength at all and any material behind the thermal front (temperatures above about 1000°F) has greatly reduced strength. If the radial erosion is 5 ft (into the footing), the pedestal will have no support and will fall. Intermediate values were based on engineering judgment; no attempt was made to analyze the complex reinforced concrete footing in detail.

REFERENCES

C-1. Drawing K-M-1736, Section E-E, looking east, Grand Gulf.

C-2. Drawing C-1048A, Grand Gulf Unit 1 - Containment Reinforced Concrete Section & Details, Rev. 18, 5-31-79, Bechtel.

C-3. Drawing C-1067C, Grand Gulf Unit 1 - RPV Pedestal Reinforced Concrete Section & Details, Rev. 13, 12-5-74, Bechtel.

C-4. Drawing C-1070A, Grand Gulf Unit 1 - Containment Concrete - RPV Pedestal Wall Developed Elevation, Plans, & Details, Rev. 13, 3-14-85, Bechtel.

C-5. Drawing C-1042, Grand Gulf Unit 1 - Containment Reinforced Concrete - Pedestal Foundation Plan at Elevation 100' 9", Rev. 8, 7-24-81, Bechtel.

C-6. By ASME, Section III, Division 2, reinforcing steel for reactor usage must conform to either ASTM A-615 or A-706 (paragraph CC-2310). The carbon content is approximately 0.33%

C-7. H. J. Hucek, The Structural Alloy Handbook, 3 vols., Battelle Memorial Institute, 1987.

C-8. G. N. Freskakis, "Behavior of Reinforced Concrete at Elevated Temperatures," Proceedings of Second ASCE Conference on Civil Engineering and Nuclear Power, Vol. 1 Materials and Structural Design, Sept. 15-17, 1980, pp 3-4-1 to 3-4-30.

C-9. T. Kanazu and Y. Aoyagi, "Mechanical Behaviours of Concrete and Reinforced Concrete at Elevated Temperatures up to 500°C," Paper H5/1, Transactions of the 8th SMiRT, 1985.

C-10. C. B. Oland, D. J. Naus, and G. C. Robinson, "Testing Program for Determining the Mechanical Properties of Concrete to Temperatures of 621°C," Oakridge National Laboratory, Oak Ridge, TN, 1980. (Paper presents test plan for LMFBR components.)

C-11. G. E. Troxell, H. E. Davis, and J. W. Kelly, Composition and Properties of Concrete, pp 248-250, McGraw Hill, New York, 1968.

C-12. P. A. Pfeiffer, J. M. Kennedy, A. H. Marchertas, "Thermal Effects in Concrete Containment Analysis," Proceedings of the Fourth Workshop on Containment Integrity, June 1988, Sandia National Laboratories, Albuquerque, New Mexico.

DISTRIBUTION:

Frank Abbey
U. K. Atomic Energy Authority
Wigshaw Lane, Culcheth
Warrington, Cheshire, WA3 4NE
ENGLAND

Kiyoharu Abe
Department of Reactor Safety
Research
Nuclear Safety Research Center
Tokai Research Establishment
JAERI
Tokai-mura, Naga-gun
Ibaraki-ken,
JAPAN

Ulvi Adalioglu
Nuclear Engineering Division
Cekmece Nuclear Research and
Training Centre
P.K.1, Havaalani
Istanbul
TURKEY

Bharat Agrawal
USNRC-RES/AEB
MS: NL/N-344

Kiyoto Aizawa
Safety Research Group
Reactor Research and Development
Project
PNC
9-13m 1-Chome Akasaka
Minatu-Ku
Tokyo
JAPAN

Oguz Akalin
Ontario Hydro
700 University Avenue
Toronto, Ontario
CANADA M5G 1X6

David Aldrich
Science Applications International
Corporation
1710 Goodridge Drive
McLean, VA 22102

Agustin Alonso
University Politecnica De Madrid
J Gutierrez Abascal, 2
28006 Madrid
SPAIN

Christopher Amos
Science Applications International
Corporation
2109 Air Park Road SE
Albuquerque, NM 87106

Richard C. Anoba
Project Engr., Corp. Nuclear Safety
Carolina Power and Light Co.
P. O. Box 1551
Raleigh, NC 27602

George Apostolakis
UCLA
Boelter Hall, Room 5532
Los Angeles, CA 90024

James W. Ashkar
Boston Edison Company
800 Boylston Street
Boston, MA 02199

Donald H. Ashton
Bechtel Power Corporation
P.O. Box 2166
Houston, TX 77252-2166

J. de Assuncao
Cabinete de Proteccao e Seguranca
Nuclear
Secretario de Estado de Energia
Ministerio da Industria
av. da Republica, 45-6°
1000 Lisbon
PORTUGAL

Mark Averett
Florida Power Corporation
P.O. Box 14042
St. Petersburg, FL 33733

Raymond O. Bagley
Northeast Utilities
P.O. Box 270
Hartford, CT 06141-0270

Juan Bagues
Consejo de Seguridad Nucleare
Sarangela de la Cruz 3
28020 Madrid
SPAIN

George F. Bailey
Washington Public Power Supply
System
P. O. Box 968
Richland, WA 99352

H. Bairiot
Belgonucleaire S A
Rue de Champ de Mars 25
B-1050 Brussels
BELGIUM

Louis Baker
Reactor Analysis and Safety
Division
Building 207
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

H-P. Balfanz
TUV-Norddeutschland
Grosse Bahnstrasse 31,
2000 Hamburg 54
FEDERAL REPUBLIC OF GERMANY

Patrick Baranowsky
USNRC-NRR/OEAB
MS: 11E-22

H. Bargmann
Dept. de Mecanique
Inst. de Machines Hydrauliques
et de Mecaniques des Fluides
Ecole Polytechnique de Lausanne
CH-1003 Lausanne
M.E. (ECUBLENS)
CH. 1015 Lausanne
SWITZERLAND

Robert A. Bari
Brookhaven National Laboratory
Building 130
Upton, NY 11973

Richard Barrett
USNRC-NRR/PRAB
MS: 10A-2

Kenneth S. Baskin
S. California Edison Company
P.O. Box 800
Rosemead, CA 91770

J. Basselier
Belgonucleaire S A
Rue du Champ de Mars 25, B-1050
Brussels
BELGIUM

Werner Bastl
Gesellschaft Fur Reaktorsicherheit
Forschungsgelande
D-8046 Garching
FEDERAL REPUBLIC OF GERMANY

Anton Bayer
BGA/ISH/ZDB
Postfach 1108
D-8042 Neuherberg
FEDERAL REPUBLIC OF GERMANY

Ronald Bayer
Virginia Electric Power Co.
P. O. Box 26666
Richmond, VA 23261

Eric S. Beckjord
Director
USNRC-RES
MS: NL/S-007

Bruce B. Beckley
Public Service Company
P.O. Box 330
Manchester, NH 03105

William Beckner
USNRC-RES/SAIB
MS: NL/S-324

Robert M. Bernero
Director
USNRC-NMSS
MS: 6A-4

Ronald Berryman [2]
Virginia Electric Power Co.
P. O. Box 26666
Richmond, VA 23261

Robert C. Bertucio
NUS Corporation
1301 S. Central Ave, Suite 202
Kent, WA 98032

John H. Bickel
EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, ID 83415

Peter Bieniarz
Risk Management Association
2309 Dietz Farm Road, NW
Albuquerque, NM 87107

Adolf Birkhofer
Gesellschaft Fur Reaktorsicherheit
Forschungsgelande
D-8046 Garching
FEDERAL REPUBLIC OF GERMANY

James Blackburn
Illinois Dept. of Nuclear Safety
1035 Outer Park Drive
Springfield, IL 62704

Dennis C. Bley
Pickard, Lowe & Garrick, Inc.
2260 University Drive
Newport Beach, CA 92660

Roger M. Blond
Science Applications Int. Corp.
20030 Century Blvd., Suite 201
Germantown, MD 20874

Simon Board
Central Electricity Generating Board
Technology and Planning Research Division
Berkeley Nuclear Laboratory
Berkeley Gloucestershire, GL139PB
UNITED KINGDOM

Mario V. Bonace
Northeast Utilities Service Company
P.O. Box 270
Hartford, CT 06101

Gary J. Boyd
Safety and Reliability Optimization Services
9724 Kingston Pike, Suite 102
Knoxville, TN 37922

Robert J. Breen
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

Charles Brinkman
Combustion Engineering
7910 Woodmont Avenue
Bethesda, MD 20814

K. J. Brinkmann
Netherlands Energy Res. Fdtn.
P.O. Box 1
1755ZG Petten NH
NETHERLANDS

Allan R. Brown
Manager, Nuclear Systems and Safety Department
Ontario Hydro
700 University Ave.
Toronto, Ontario M5G1X6
CANADA

Robert G. Brown
TENERA L.P.
1340 Saratoga-Sunnyvale Rd.
Suite 206
San Jose, CA 95129

Sharon Brown
EI Services
1851 So. Central Place, Suite 201
Kent, WA 98031

Ben Buchbinder
NASA, Code QS
600 Maryland Ave. SW
Washington, DC 20546

R. H. Buchholz
Nutech
6835 Via Del Oro
San Jose, CA 95119

Robert J. Budnitz
Future Resources Associates
734 Alameda
Berkeley, CA 94707

Gary R. Burdick
USNRC-RES/DSR
MS: NL/S-007

Arthur J. Buslik
USNRC-RES/PRAB
MS: NL/S-372

M. Bustraan
Netherlands Energy Res. Fdtn.
P.O. Box 1
1755ZG Petten NH
NETHERLANDS

Nigel E. Buttery
Central Electricity Generating
Board
Booths Hall
Chelford Road, Knutsford
Cheshire, WA168QG
UNITED KINGDOM

Jose I. Calvo Molins
Probabilistic Safety Analysis
Group
Consejo de Seguridad Nuclear
Sor Angela de la Cruz 3, Pl. 6
28020 Madrid
SPAIN

J. F. Campbell
Nuclear Installations Inspectorate
St. Peters House
Balliol Road, Bootle
Merseyside, L20 3LZ
UNITED KINGDOM

Kenneth S. Canady
Duke Power Company
422 S. Church Street
Charlotte, NC 28217

Lennart Carlsson
IAEA A-1400
Wagramerstrasse 5
P.O. Box 100
Vienna, 22
AUSTRIA

Annick Carnino
Electricite de France
32 Rue de Monceau 8EME
Paris, F5008
FRANCE

G. Caropreso
Dept. for Envir. Protect. & Hlth.
ENEA Cre Casaccia
Via Anguillarese, 301
00100 Roma
ITALY

James C. Carter, III
TENERA L.P.
Advantage Place
308 North Peters Road
Suite 280
Knoxville, TN 37922

Eric Cazzoli
Brookhaven National Laboratory
Building 130
Upton, NY 11973

John G. Cesare
SERI
Director Nuclear Licensing
5360 I-55 North
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
P.O. Box 3
Lungtan, 325
TAIWAN

J. R. Chapman
Yankee Atomic Electric Company
1671 Worcester Road
Framingham, MA 01701

Robert F. Christie
Tennessee Valley Authority
400 W. Summit Hill Avenue, W10D190
Knoxville, TN 37902

T. Cianciolo
BWR Assistant Director
ENEA DISP TX612167 ENEUR
Rome
ITALY

Thomas Cochran
Natural Resources Defense Council
1350 New York Ave. NW, Suite 300
Washington, D.C. 20005

Frank Coffman
USNRC-RES/HFB
MS: NL/N-316

Larry Conradi
NUS Corporation
16835 W. Bernardo Drive
Suite 202
San Diego, CA 92127

Peter Cooper
U.K. Atomic Energy Authority
Wigshaw Lane, Culcheth
Warrington, Cheshire, WA3 4NE
UNITED KINGDOM

C. Allin Cornell
110 Coquito Way
Portola Valley, CA 94025

Michael Corradini
University of Wisconsin
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
USNRC-RES/SSEB
MS: NL/S-217A

George R. Crane
1570 E. Hobble Creek Dr.
Springville, UT 84663

Mat Crawford
SERI
5360 I-55 North
Jackson, MS 39211

Michael C. Cullingford
Nuclear Safety Division
IAEA
Wagramerstrasse, 5
P.O. Box 100
A-1400 Vienna
AUSTRIA

Garth Cummings
Lawrence Livermore Laboratory
L-91, Box 808
Livermore, CA 94526

Mark A. Cunningham
USNRC-RES/PRAB
MS: NL/S-372

James J. Curry
7135 Salem Park Circle
Mechanicsburg, PA 17055

Peter Cybulskis
Battelle Columbus Division
505 King Avenue
Columbus, OH 43201

Peter R. Davis
PRD Consulting
1935 Sabin 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
Columbus, OH 43201

Vernon Denny
Science Applications Int. Corp.
5150 El Camino Real, Suite 3
Los Altos, CA 94303

J. Devooget
Faculte des Sciences Appliques
Universite Libre de Bruxelles
av. Franklin Roosevelt
B-1050 Bruxelles
BELGIUM

R. A. Diederich
Supervising Engineer
Environmental Branch
Philadelphia Electric Co.
2301 Market St.
Philadelphia, PA 19101

Raymond DiSalvo
Battelle Columbus Division
505 King Avenue
Columbus, OH 43201

Mary T. Drouin
Science Applications International
Corporation
2109 Air Park Road S.E.
Albuquerque, NM 87106

Andrzej Drozd
Stone and Webster
Engineering Corp.
243 Summer Street
Boston, MA 02107

N. W. Edwards
NUTECH
145 Martinville Lane
San Jose, CA 95119

Ward Edwards
Social Sciences Research Institute
University of Southern California
Los Angeles, CA 90089-1111

Joachim Ehrhardt
Kernforschungszentrum Karlsruhe/INR
Postfach 3640
D-7500 Karlsruhe 1
FEDERAL REPUBLIC OF GERMANY

Adel A. El-Bassioni
USNRC-NRR/PRAB
MS: 10A-2

J. Mark Elliott
International Energy Associates,
Ltd., Suite 600
600 New Hampshire Ave., NW
Washington, DC 20037

Farouk Eltawila
USNRC-RES/AEB
MS: NL/N-344

Mike Epstein
Fauske and Associates
P. O. Box 1?25
16W070 West 83rd Street
Burr Ridge, IL 60521

Malcolm L. Ernst
USNRC-RGN II

F. R. Farmer
The Long Wood, Lyons Lane
Appleton, Warrington
WA4 5ND
UNITED KINGDOM

P. Fehrenback
Atomic Energy of Canada, Ltd.
Chalk River Nuclear Laboratories
Chalk River Ontario, K0J1P0
CANADA

P. Ficara
ENEA Cre Casaccia
Department for Thermal Reactors
Via Anguillarese, 301
00100 ROMA
ITALY

A. Fiege
Kernforschungszentrum
Postfach 3640
D-7500 Karlsruhe
FEDERAL REPUBLIC OF GERMANY

John Flack
USNRC-RES/SAIB
MS: NLS-324

George F. Flanagan
Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37831

Karl N. Fleming
Pickard, Lowe & Garrick, Inc.
2260 University Drive
Newport Beach, CA 92660

Terry Foppe
Rocky Flats Plant
P. O. Box 464, Building T886A
Golden, CO 80402 64

Joseph R. Fragola
Science Applications International
Corporation
274 Madison Avenue
New York, NY 10016

Wiktor Frid
Swedish Nuclear Power Inspectorate
Division of Reactor Technology
P. O. Box 27106
S-102 52 Stockholm
SWEDEN

James Fulford
NUS Corporation
910 Clopper Road
Gaithersburg, MD 20878

Urho Fulkkinen
Technical Research Centre of
Finland
Electrical Engineering Laboratory
Otakaari 7 B
SF-02150 Espoo 15
FINLAND

J. B. Fussell
JBF Associates, Inc.
1630 Downtown West Boulevard
Knoxville, TN 37919

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
Brookhaven National Laboratory
Upton, NY 11973

James C. Glynn
USNRC-RES/PRAB
MS: NL/S-372

P. Govaerts
Departement de la Surete Nucleaire
Association Vincotte
avenue du Roi 157
B-1060 Bruxelles
BELGIUM

George Greene
Building 820M
Brookhaven National Laboratory
Upton, NY 11973

Carrie Grimshaw
Brookhaven National Laboratory
Building 130
Upton, NY 11973

H. J. Van Grol
Energy Technology Division
Energieonderzoek Centrum Nederland
Westerduinweg 3
Postbus 1
NL-1755 Petten ZG
NETHERLANDS

Sergio Guarro
Lawrence Livermore Laboratories
P. O. Box 808
Livermore, CA 94550

Sigfried Hagen
Kernforschungzentrum Karlsruhe
P. O. Box 3640
D-7500 Karlsruhe 1
FEDERAL REPUBLIC OF GERMANY

L. Hammar
Statens Karnkraftinspektion
P.O. Box 27106
S-10252 Stockholm
SWEDEN

Stephen Hanauer
Technical Analysis Corp.
6723 Whittier Avenue
Suite 202
McLean, VA 22101

Brad Hardin
USNRC-RES/TRAB
MS: NL/S-169

R. J. Hardwich, Jr.
Virginia Electric Power Co.
P.O. Box 26666
Richmond, Va 23261

Michael R. Haynes
UKAEA Harwell Laboratory
Oxfordshire
Didcot, Oxon., OX11 ORA
ENGLAND

Michael J. Hazzan
Stone & Webster
3 Executive Campus
Cherry Hill, NJ 08034

A. Hedgran
Royal Institute of Technology
Nuclear Safety Department
Bunellvagen 60
10044 Stockholm
SWEDEN

Sharif Heger
UNM Chemical and Nuclear
Engineering Department
Farris Engineering
Room 209
Albuquerque, NM 87131

Jon C. Helton
Dept. of Mathematics
Arizona State University
Tempe, AZ 85287

Robert E. Henry
Fauske and Associates, Inc.
16W070 West 83rd Street
Burr Ridge, IL 60521

P. M. Herttrich
Federal Ministry for the
Environment, Preservation of
Nature and Reactor Safety
Husarenstrasse 30
Postfach 120629
D-5300 Bonn 1
FEDERAL REPUBLIC OF GERMANY

F. Heuser
Giesellschaft Fur Reaktorsicherheit
Forschurgsgelande
D-8046 Garching
FEDERAL REPUBLIC OF GERMANY

E. F. Hicken
Giesellschaft Fur Reaktorsicherheit
Forschungsgelande
D-8046 Garching
FEDERAL REPUBLIC OF GERMANY

D. J. Higson
Radiological Support Group
Nuclear Safety Bureau
Australian Nuclear Science and
Technology Organisation
P.O. Box 153
Rosebery, NSW 2018
AUSTRALIA

Daniel Hirsch
University of California
A. Stevenson Program on
Nuclear Policy
Santa Cruz, CA 95064

H. Hirschmann
Hauptabteilung Sicherheit und
Umwelt
Swiss Federal Institute for
Reactor Research (EIR)
CH-5303 Wurenlingen
SWITZERLAND

Mike Hitchler
Westinghouse Electric Corp.
Savanna River Site
Aiken, SC 29808

Richard Hobbins
EG&G Idaho, Inc.
P. O. Box 1625
Idaho Falls, ID 83415

Steven Hodge
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
D-8046 Garching
FEDERAL REPUBLIC OF GERMANY

Peter Hoffmann
Kernforschingszentrum Karlsruhe
Institute for Material
Und Festkorperforsching I
Postfach 3640
D-7500 Karlsruhe 1
FEDERAL REPUBLIC OF GERMANY

N. J. Holloway
UKAEA Safety and Reliability
Directorate
Wigshaw Lane, Culcheth
Warrington, Cheshire, WA34NE
UNITED KINGDOM

Stephen C. Hora
University of Hawaii at Hilo
Division of Business Administration
and Economics
College of Arts and Sciences
Hilo, HI 96720-4091

J. Peter Hoseman
Swiss Federal Institute for
Reactor Research
CH-5303, Wurenlingen
SWITZERLAND

Thomas C. Houghton
KMC, Inc.
1747 Pennsylvania Avenue, NW
Washington, DC 20006

Dean Houston
USNRC-ACRS
MS: P-315

Der Yu Hsia
Taiwan Atomic Energy Council
67, Lane 144, Keelung Rd.
Sec. 4
Taipei
TAIWAN

Alejandro Huerta-Bahena
National Commission on Nuclear
Safety and Safeguards (CNSNS)
Insurgentes Sur N. 1776
Col. Florida
C. P. 04230 Mexico, D.F.
MEXICO

Kenneth Hughey [2]
SERI
5360 I-55 North
Jackson, MS 39211

Won-Guk Hwang
Kzunghee University
Yongin-Kun
Kyunggi-Do 170-23
KOREA

Michio Ichikawa
Japan Atomic Energy Research Institute
Dept. of Fuel Safety Research
Tokai-Mura, Naka-Gun
Ibaraki-Ken, 319-1
JAPAN

Sanford Israel
USNRC-AEOD/ROAB
MS: MNBB-9715

Krishna R. Iyengar
Louisiana Power and Light
200 A Huey P. Long Avenue
Gretna, LA 70053

Jerry E. Jackson
USNRC-RES
MS: NL/S-302

R. E. Jaquith
Combustion Engineering, Inc.
1000 Prospect Hill Road
M/C 9490-2405
Windsor, CT 06095

S. E. Jensen
Exxon Nuclear Company
2101 Horn Rapids Road
Richland, WA 99352

Kjell Johannson
Studsvik Energiteknik AB
S-611 82, Nykoping
SWEDEN

Richard John
SSM, Room 102
927 W. 35th Place
USC, University Park
Los Angeles, CA 90089-0021

D. H. Johnson
Pickard, Lowe & Garrick, Inc.
2260 University Drive
Newport Beach, CA 92660

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
Gesellschaft 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
Los Angeles, CA 90024

Walter Kato
Brookhaven National Laboratory
Associated Universities, Inc.
Upton, NY 11973

M. S. Kazimi
MIT, 24-219
Cambridge, MA 02139

Ralph L. Keeney
101 Lombard Street
Suite 704W
San Francisco, CA 94111

Henry Kendall
Executive Director
Union of Concerned Scientists
Cambridge, MA

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
Winfrith, Dorchester
Dorset DT2 8DH
ENGLAND

Ryohei 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
2109 Air Park Road, S.E.
Albuquerque, NM 87106

S. Kondo
Department of Nuclear Engineering
Facility of Engineering
University of Tokyo
3-1, Hongo 7, Bunkyo-ku
Tokyo
JAPAN

Herbert J. C. Kouts
Brookhaven National Laboratory
Building 179C
Upton, NY 11973

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
2109 Air Park Road S.E.
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

Timothy J. Leahy
EI Services
1851 South Central Place, Suite 201
Kent, WA 98031

John C. Lee
University of Michigan
North Campus
Dept. of Nuclear Engineering
Ann Arbor, MI 48109

Tim Lee
USNRC-RES/RPSB
MS: NL/N-353

Mark T. Leonard
Science Applications International Corporation
2109 Air Park Road, SE
Albuquerque, NM 87106

Leo LeSage
Director, Applied Physics Div.
Argonne National Laboratory
Building 208, 9700 South Cass Ave.
Argonne, IL 60439

Milton Levenson
Bechtel Western Power Company
50 Beale St.
San Francisco, CA 94119

Librarian
NUMARC/USCEA
1776 I Street NW, Suite 400
Washington, DC 80006

Eng Lin
Taiwan Power Company
242, Roosevelt Rd., Sec. 3
Taipei
TAIWAN

N. J. Liparulo
Westinghouse Electric Corp.
P. O. Box 355
Pittsburgh, PA 15230

Y. H. (Ben) Liu
Department of Mechanical Engineering
University of Minnesota
Minneapolis, MN 55455

Bo Liwnang
IAEA A-1400
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

Walter Lowenstein
Electric Power Research Institute
3412 Hillview Avenue
P. O. Box 10412
Palo Alto, CA 94303

William J. Luckas
Brookhaven National Laboratory
Building 130
Upton, 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
Finland
Lonnrotinkatu 37, P. O. Box 169
SF-00181 Helsinki 18
FINLAND

Roger J. Mattson
SCIENTECH Inc.
11821 Parklawn Dr.
Rockville, MD 20852

Donald McPherson
USNRC-NRR/DONRR
MS: 12G-18

Jim Metcalf
Stone and Webster Engineering
Corporation
245 Summer St.
Boston, MA 02107

Mary Meyer
A-1, MS F600
Los Alamos National Laboratory
Los Alamos, NM 87545

Ralph Meyer
USNRC-RES/AEB
MS: NL/N-344

Charles Miller
8 Hastings Rd.
Momsey, NY 10952

Joseph Miller
Gulf States Utilities
P. O. Box 220
St. Francisville, LA 70775

William Mims
Tennessee Valley Authority
400 West Summit Hill Drive.
W10D199C-K
Knoxville, TN 37902

Jocelyn Mitchell
USNRC-RES/SAIB
MS: NL/S-324

Kam Mohktarian
CBI Na-Con Inc.
800 Jorie Blvd.
Oak Brook, IL 60521

James Moody
P.O. Box 641
Rye, NH 03870

S. Mori
Nuclear Safety Division
OECD Nuclear Energy Agency
38 Blvd. Suchet
75016 Paris
FRANCE

Walter B. Murfin
P.O. Box 550
Mesquite, NM 88048

Joseph A. Murphy
USNRC-RES/DSR
MS: NL/S-007

V. I. Nath
Safety Branch
Safety Engineering Group
Sheridan Park Research Community
Mississauga, Ontario L5K 1B2
CANADA

Susan J. Niemczyk
1545 18th St. NW, #112
Washington, DC 20036

Pradyot K. Niyogi
USDOE-Office of Nuclear Safety
Washington, DC 20545

Paul North
EG&G Idaho, Inc.
P. O. Box 1625
Idaho Falls, ID 83415

Edward P. O'Donnell
Ebasco Services, Inc.
2 World Trade Center, 89th Floor
New York, NY 10048

David Okrent
UCLA
Boelter Hall, Room 5532
Los Angeles, CA 90024

Robert L. Olson
Tennessee Valley Authority
400 West Summit Hill Rd.
Knoxville, TN 37902

Simon Ostrach
Case Western Reserve University
418 Glenman Bldg.
Cleveland, OH 44106

D. Paddleford
Westinghouse Electric Corporation
Savannah River Site
Aiken, SC 29808

Robert L. Palla, Jr.
USNRC-NRR/PRAB
MS: 10A-2

Chang K. Park
Brookhaven National Laboratory
Building 130
Upton, NY 11973

Michael C. Parker
Illinois Department of Nuclear
Safety
1035 Outer Park Dr.
Springfield, IL 62704

Gareth Parry
NUS Corporation
910 Clopper Road
Gaithersburg, MD 20878

J. Pelce
Departement de Surete Nucleaire
IPSN
Centre d'Estudes Nucleaires du CEA
B.P. no. 6, Cedex
F-92260 Fontenay-aux-Roses
FRANCE

G. Petrangeli
ENEA Nuclear Energy ALT Disp
Via V. Brancati, 48
00144 Rome
ITALY

Marty Plys
Fauske and Associates
16W070 West 83rd St.
Burr Ridge, IL 60521

Mike Podowski
Department of Nuclear Engineering
and Engineering Physics
RPI
Troy, NY 12180-3590

Robert D. Pollard
Union of Concerned Scientists
1616 P Street, NW, Suite 310
Washington, DC 20036

R. Potter
UK Atomic Energy Authority
Winfrith, Dorchester
Dorset, DT2 8DH
UNITED KINGDOM

William T. Pratt
Brookhaven National Laboratory
Building 130
Upton, NY 11973

M. Preat
Chef du Service Surete Nucleaire et
Assurance Qualite
TRACTEBEL
Bd. du Regent 8
B-100 Bruxells
BELGIUM

David Pyatt
USDOE
MS: EH-332
Washington, DC 20545

William Raisin
NUMAEC
1726 M St. NW
Suite 904
Washington, DC 20036

Joe Rashid
ANATECH Research Corp.
3344 N. Torrey Pines Ct.
Suite 1320
La Jolla, CA 90237

Dale M. Rasmuson
USNRC-RES/PRAB
MS: NL/S-372

Ingvard Rasmussen
Riso National Laboratory
Postbox 49
DK-4000, Roskilde
DENMARK

Norman C. Rasmussen
Massachusetts Institute of
Technology
77 Massachusetts Avenue
Cambridge, MA 02139

John W. Reed
Jack R. Benjamin & Associates, Inc.
444 Castro St., Suite 501
Mountain View, CA 94041

David B. Rhodes
Atomic Energy of Canada, Ltd.
Chalk River Nuclear Laboratories
Chalk River, Ontario K0J1P0
CANADA

Dennis Richardon
Westinghouse Electric Corporation
P.O. Box 355
Pittsburgh, PA 15230

Doug Richeard
Virginia Electric Power Co.
P.O.Box 26666
Richmond, VA 23261

Robert Ritzman
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94304

Richard Robinson
USNRC-RES/PRAB
MS: NL/S-372

Jack E. Rosenthal
USNRC-AEOD/ROAB
MS: MNBB-9715

Denwood F. Ross
USNRC-RES
MS: NL/S-007

Frank Rowsome
9332 Fern Hollow Way
Gaithersburg, MD 20879

Wayne Russell
SERI
5360 I-55 North
Jackson, MS 39211

Jorma V. Sandberg
Finnish Ctr. Rad. Nucl. and Safety
Department of Nuclear Safety
P.O. Box 268
SF-00101 Helsinki
FINLAND

G. Saponaro
ENEA Nuclear Engineering Alt.
Zia V Brancati 48
00144 ROME
ITALY

M. Sarran
United Engineers
P. O. Box 8223
30 S 17th Street
Philadelphia, PA 19101

J. Schroeder
EG&G Idaho, Inc.
P. O. Box 1625
Idaho Falls, ID 83415

Marty Sattison
EG&G Idaho, Inc.
P. O. Box 1625
Idaho Falls, ID 83415

George D. Sauter
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

Jorge Schulz
Bechtel Western Power Corporation
50 Beale Street
San Francisco, CA 94119

B. R. Sehgal
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

Subir Sen
Bechtel Power Corp.
15740 Shady Grove Road
Location 1A-7
Gaithersburg, MD 20877

S. Serra
Ente Nazionale per l'Energia
Electtrica (ENEL)
via G. B. Martini 3
Rome
ITALY

Bonnie J. Shapiro
Science Applications International
Corporation
360 Bay Street
Suite 200
Augusta, GA 30901

H. Shapiro
Licensing and Risk Branch
Atomic Energy of Canada Ltd.
Sheridan Park Research Community
Mississauga, Ontario L5K 1B2
CANADA

Dave Sharp
Westinghouse Savannah River Co.
Building 773-41A, P. O. Box 616
Aiken, SC 29802

John Sherman
Tennessee Environmental Council
1719 West End Avenue, Suite 227
Nashville, TN 37203

Brian Sheron
USNRC-RES/DSR
MS: NL/N-007

Rick Sherry
JAYCOR
P. O. Box 85154
San Diego, CA 92138

Steven C. Sholly
MHB Technical Associates
1723 Hamilton Avenue, Suite K
San Jose, CA 95125

Louis M. Shotkin
USNRC-RES/RPSB
MS: NL/N-353

M. Siebertz
Chef de la Section Surete' des
Reacteurs
CEN/SCK
Boeretang, 200
B-2400 Mol
BELGIUM

Melvin Silberberg
USNRC-RES/DE/WNB
MS: NL/S-260

Gary Smith
SERI
5360 I-55 North
Jackson, MS 39211

Gary L. Smith
Westinghouse Electric Corporation
Hanford Site
Box 1970
Richland, WA 99352

Lanny N. Smith
Science Applications International
Corporation
2109 Air Park Road SE
Albuquerque, NM 87106

K. Soda
Japan Atomic Energy Res. Inst.
Tokai-Mura Naka-Gun
Ibaraki-Ken 319-11
JAPAN

David Sommers
Virginia Electric Power Company
P. O. Box 26666
Richmond, VA 23261

Herschel Spector
New York Power Authority
123 Main Street
White Plains, NY 10601

Themis P. Speis
USNRC-RES
MS: NL/S-007

Klaus B. Stadie
OECD-NEA, 38 Bld. Suchet
75016 Paris
FRANCE

John Stetkar
Pickard, Lowe & Garrick, Inc.
2216 University Drive
Newport Beach, CA 92660

Wayne L. Stiede
Commonwealth Edison Company
P.O. Box 767
Chicago, IL 60690

William Stratton
Stratton & Associates
2 Acoma Lane
Los Alamos, NM 87544

Soo-Pong Suk
Korea Advanced Energy Research Institute
P. O. Box 7
Daeduk Danji, Chungnam 300-31
KOREA

W. P. Sullivan
GE Nuclear Energy
175 Curtner Ave., M/C 789
San Jose, CA 95125

Tony Taig
U.K. Atomic Energy Authority
Wigshaw Lane, Culcheth
Warrington, Cheshire, WA3 4NE
UNITED KINGDOM

John Taylor
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

Harry Teague
U.K. Atomic Energy Authority
Wigshaw Lane, Culcheth
Warrington, Cheshire, WA3 4NE
UNITED KINGDOM

Technical Library
Electric Power Research Institute
P.O. Box 10412
Palo Alto, CA 94304

Mark I. Temme
General Electric Inc.
P.O. Box 3508
Sunnyvale, CA 94088

T. G. Theofanous
University of California, S.B.
Department of Chemical and Nuclear Engineering
Santa Barbara, CA 93106

David Teolis
Westinghouse-Bettis Atomic Power Laboratory
P. O. Box 79, ZAP 34N
West Mifflin, PA 15122-0079

Ashok C. Thadani
USNRC-NRR/SAD
MS: 7E-4

Garry Thomas
L-499 (Bldg. 490)
Lawrence Livermore National Laboratory
7000 East Ave.
P.O. Box 808
Livermore, CA 94550

Gordon Thompson
Institute for Research and Security Studies
27 Ellworth Avenue
Cambridge, MA 02139

Grant Thompson
League of Women Voters
1730 M. Street, NW
Washington, DC 20036

Arthur Tingle
Brookhaven National Laboratory
Building 130
Upton, NY 11973

Rich Toland
United Engineers and Construction
30 S. 17th St., MS 4V7
Philadelphia, PA 19101

Brian J. R. Tolley
DG/XII/D/1
Commission of the European Communities
Rue de la Loi, 200
B-1049 Brussels
BELGIUM

David R. Torgerson
Atomic Energy of Canada Ltd.
Whiteshell Nuclear
Research Establishment
Pinawa, Manitoba, ROE 1LO
CANADA

Alfred F. Torri
Pickard, Lowe & Garrick, Inc.
191 Calle Magdalena, Suite 290
Encinitas, CA 92024

Klau Trambauer
Gesellschaft Fur Reaktorsicherheit
Forschungsgelande
D-8046 Garching
FERERAL REPUBLIC OF GERMANY

Nicholas Tsoulfanidis
Nuclear Engineering Dept.
University of Missouri-Rolla
Rolla, MO 65401-0249

Chao-Ch'n Tung
c/o H.B. Bengelsdorf
ERC Environmental Services Co.
P. O. Box 10130
Fairfax, A 22030

Brian D. Turland
UKAEA Culham Laboratory
Abingdon, Oxon OX14 3DB
ENGLAND

Takeo Uga
Japan Institute of Nuclear Safety
Nuclear Power Engineering Test
Center
3-6-2, Toranomon
Minato-ku, Tokyo 108
JAPAN

Stephen D Unwin
Battelle Columbus Division
505 King Avenue
Columbus, OH 43201

A. Valeri
DISP
ENEA
Via Vitaliano Brancati, 48
I-00144 Rome
ITALY

Harold VanderMolen
USNRC-RES/PRAB
MS: NL/S-372

G. Bruce Varnado
ERC International
1717 Louisiana Blvd. NE, Suite 202
Albuquerque, NM 87110

Jussi K. Vaurio
Imatran Voima Oy
Loviisa NPS
SF-07900 Loviisa
FINLAND

William E. Vesely
Science Applications International
Corporation
2929 Kenny Road, Suite 245
Columbus, OH 43221

J. I. Villadoniga Tallon
Div. of Analysis and Assessment
Consejo de Seguridad Nuclear
c/ Sor Angela de la Cruz, 3
28020 Madrid
SPAIN

Willem F. Vinck
Kapellestract 25
1980
Tervuren
BELGIUM

R. Virolainen
Office of Systems Integration
Finnish Centre for Radiation and
Nuclear Safety
Department of Nuclear Safety
P.O. Box 268
Kumpulantie 7
SF-00520 Helsinki
FINLAND

Raymond Viskanta
School of Mechanical Engineering
Purdue University
West Lafayette, IN 47907

S. Visweswaran
General Electric Company
175 Curtner Avenue
San Jose, CA 95125

Truong Vo
Pacific Northwest Laboratory
Battelle Blvd.
Richland, WA 99352

Richard Vogel
Electric Power Research Institute
P. O. Box 10412
Palo Alto, CA 94303

G. Volta
Engineering Division
CEC Joint Research Centre
CP No. 1
I-21020 Ispra (Varese)
ITALY

Ian B. Wall
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

Adolf Walser
Sargent and Lundy Engineers
55 E. Monroe Street
Chicago, IL 60603

Edward Warman
Stone & Webster Engineering Corp.
P.O. Box 2325
Boston, MA 02107

Norman Weber
Sargent & Lundy Co.
55 E. Monroe Street
Chicago, IL 60603

Lois Webster
American Nuclear Society
555 N. Kensington Avenue
La Grange Park, IL 60525

Wolfgang Werner
Gesellschaft Fur Reaktorsicherheit
Forschungsgelande
D-8046 Garching
FEDERAL REPUBLIC OF GERMANY

Don Wesley
IMPELL
1651 East 4th Street
Suite 210
Santa Ana, CA 92701

Detlof von Winterfeldt
Institute of Safety and Systems Management
University of Southern California
Los Angeles, CA 90089-0021

Pat Worthington
USNRC-RES/AEB
MS: NL/N-344

John Wreathall
Science Applications International Corporation
2929 Kenny Road, Suite 245
Columbus, OH 43221

D. J. Wren
Atomic Energy of Canada Ltd.
Whiteshell Nuclear Research Establishment
Pinawa, Manitoba, ROE 1LO
CANADA

Roger Wyrick
Inst. for Nuclear Power Operations
1100 Circle 75 Parkway, Suite 1500
Atlanta, GA 30339

Kun-Joong Yoo
Korea Advanced Energy Research Institute
P. O. Box 7
Daeduk Danji, Chungnam 300-31
KOREA

Faith Young
Energy People, Inc.
Dixon Springs, TN 37057

Jonathan Young
R. Lynette and Associates
15042 Northeast 40th St.
Suite 206
Redmond, WA 98052

C. Zaffiro
Division of Safety Studies
Directorate for Nuclear Safety and Health Protection
Ente Nazionale Energie Alternative
Via Vitaliano Brancati, 48
I-00144 Rome
ITALY

Mike Zentner
Westinghouse Hanford Co.
P. O. Box 1970
Richland, WA 99352

X. Zikidis
Greek Atomic Energy Commission
Agia Paraskevi, Attiki
Athens
GREECE

Bernhard Zuczera
Kernforschungszentrum
Postfach 3640
D-7500 Karlsruhe
FEDERAL REPUBLIC OF GERMANY

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R. J. Breeding, F. T. Harper, T. D. Brown, J. J. Gregory,
A. C. Payne, E. D. Gorham, W. Murfin,* C. N. Amos**

*Technadyne
**Science Applications International Corporation

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11. ABSTRACT (200 words or less)

In support of the Nuclear Regulatory Commission's (NRC's) assessment of the risk from severe accidents at commercial nuclear power plants in the U.S. reported in NUREG-1150, the Severe Accident Risk Reduction Program (SAARP) has completed a revised calculation of the risk to the general public from severe accidents at five nuclear power plants: Surry, Sequoyah, Zion, Peach Bottom and Grand Gulf.

The emphasis in this risk analysis was not on determining a "so-called" point estimate of risk. Rather, it was to determine the distribution of risk, and to discover the uncertainties that account for the breadth of this distribution. Off-site risk initiation by events, both internal to the power station and external to the power station were assessed.

Much of the important input to the logic models was generated by expert panels. This document presents the distributions and the rationale supporting the distributions for the questions posed to the Structural Response Panel.

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