Evaluation of Severe Accident Risks: Quantification of Major Input Parameters

Experts' Determination of Containment Loads and
Molten Core Containment Interaction Issues

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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 Containment Loads and Molten Core/Containment Interaction Expert Panel Elicitation are presented in this part of Volume 2 of NUREG/CR-4551. The Containment Loads Expert Panel considered seven issues:

1. Hydrogen Phenomena at Grand Gulf;
2. Hydrogen Burn at Vessel Breach at Sequoyah;
3. BWR Reactor Building Failure Due to Hydrogen;
4. Grand Gulf Containment Loads at Vessel Breach;
5. Pressure Increment in the Sequoyah Containment at Vessel Breach;
6. Loads at Vessel Breach: Surry;
7. Pressure Increment in the Zion Containment at Vessel Breach.

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.

The Molten Core/Containment Interaction Panel considered three issues. The results of the following two of these issues are presented in this document:

1. Peach Bottom Drywell Shell Meltthrough;
2. Grand Gulf Pedestal Erosion.

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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 elicitations from the Containment Loads Expert Panel and the Molten Core/Concrete Interaction 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"; the Revision 1 designator is used to maintain consistency with NUREG-4550 documents.

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

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 (EVNTRE)," Sandia National Laboratories, Albuquerque, NM, 1988.

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.

SUPPORT DOCUMENTS TO NUREG-1150

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

ACKNOWLEDGMENTS

As authors of this report, we acknowledge the help of all of the participants in the expert judgment elicitation process including the expert panel; the normative experts; the substantive experts; and the utility, industry, national laboratory and other experts who attended the meetings. While we wrote most of the actual report, the members of the expert panels provided us with most of the technical substance. We would particularly like to thank Steve Hora of the University of Hawaii for his role in developing the expert judgment elicitation methodology, Ralph Keeney of the University of Southern California for his assistance in directing the elicitation process, and the following people from Sandia National Laboratories: Reeta Garber for assistance in preparing this report; Ann Shiver for aggregating the results and visually presenting these in figures; and Timothy Wheeler for providing not only the template for this report but also for much of the prose in the introductory sections. We also appreciate the support of Joseph Murphy, Mark Cunningham, and P. K. Niyogi of the NRC.

ACRONYMS AND INITIALISMS

ACRS	Advisory Committee on Reactor Safeguards
ADS	automatic depressurization system
AICC	adiabatic isochoric complete combustion
AIChE	American Institute of Chemical Engineers
ANL	Argonne National Laboratory
ANS	American Nuclear Society
APET	accident progression event tree
ASME	American Society of Mechanical Engineers
ATWS	anticipated transient without scram
BNL	Brookhaven National Laboratory
BWR	boiling water reactor
CCI	core-concrete interaction
CDF	cumulative distribution function
CRD	control rod drive
DBA	design basis accident
DCH	direct containment heating
DDT	deflagration-to-detonation transition
DF	decontamination factor
DOE	Department of Energy
DWM	drywell meltthrough
FCI	fuel coolant interaction
FAI	Fauske and Associates, Inc.
FSAR	final safety analysis report
HPME	high pressure melt injection
IC	ice condenser
IDCOR	Industry Degraded Core Rulemaking
INEL	Idaho National Engineering Laboratory
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
OP	overpressure
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
SAIC	Science Applications International Corporation
S&W	Stone and Webster
SGTR	steam generator tube rupture
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-1150¹ 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 which 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;
 - 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, accident progression and source term 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 Containment Loads Expert Panel and the Molten Core/Containment Interaction 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 for NUREG-1150 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. The applicability of the data is questionable;
4. Existing data needs 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.

There were seven containment loads issues and two molten core/containment interaction issues that were considered important enough to be the subject

of a formal expert judgment elicitation. Table 1.1 lists the containment loads issues and Table 1.2 lists the molten core/containment interaction issues. The original list of containment loads issues was slightly different than that presented in Table 1.1. The experts deleted the pressure rise at vessel breach issues for Peach Bottom and LaSalle and expanded the loads at vessel breach for pressurized water reactor (PWR) issue into three issues: loads at vessel breach for Surry, Sequoyah, and Zion. (This document will not present any results for the LaSalle issues that were considered at the time of the expert elicitations.)

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 Containment Loads Expert Panel and the Molten Core/Containment 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 use to aggregate the expert's distributions, the aggregated distributions, and written accounts of each individual response to the question. The individual expert's narrative include 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. Section 6 contains conclusions and recommendations. The conclusions given in Section 6 relate to the value of the products of the study and the effectiveness of the process.

Table 1.1
Containment Loads Issues Considered for Expert Judgment Elicitation

Issue	Applicable Plants
1. Hydrogen Phenomena at Grand Gulf	Grand Gulf
2. Hydrogen Burn at Vessel Breach at Sequoyah	Sequoyah
3. BWR Reactor Building Failure Due to Hydrogen	Peach Bottom
4. Grand Gulf Containment Loads at Vessel Breach	Grand Gulf
5. Pressure Increment in the Sequoyah Containment at Vessel Breach	Sequoyah
6. Loads at Vessel Breach: Surry	Surry
7. Pressure Increment in the Zion Containment at Vessel Breach	Zion

Note: LaSalle Reactor Building Failure was addressed by the panel. The results will be reported in the LaSalle documentation.

Table 1.2
Molten Core/Containment Issues Considered
for Expert Judgment Elicitation

Issue	Applicable Plants
1. Peach Bottom Drywell Shell Meltthrough	Peach Bottom
2. Grand Gulf Pedestal Erosion	Grand Gulf

Note: LaSalle Pedestal Erosion was addressed by the panel. The results will be reported in the LaSalle documentation.

REFERENCE

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., 1989.

2. EXPERT CREDENTIALS

The objective for selecting the panel members was to obtain experts with as much expertise as possible in the fields of containment loads and molten core/containment interactions. 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 which 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 containment loads (CL) and molten core/containment interaction (MCCI) issues were:

Louis Baker Jr. (CL)	Argonne National Laboratory
Kenneth Bergeron (CL)	Sandia National Laboratories
Theodore Ginsberg (CL)	Brookhaven National Laboratory
James Metcalf (CL)	Stone and Webster Engineering Corporation
Martin Plys (CL)	Fauska and Associates
Martin Sherman (CL)	Sandia National Laboratories
Alfred Torri (CL)	Pickard, Lowe, and Garrick, Inc.
Patricia Worthington (CL)	U.S. Nuclear Regulatory Commission
David Bradley (MCCI)	Sandia National Laboratories
Michael Corradini (MCCI)	University of Wisconsin
George Greene (MCCI)	Brookhaven National Laboratory
Michael J. Hazzan (MCCI)	Stone and Webster Engineering Corporation
Mujid Kazimi (MCCI)	Massachusetts Institute of Technology
Bal Raj Sehgal (MCCI)	Electric Power Research Institute

Brief biographical sketches of the experts are presented below:

Containment Loads Expert Panel

Louis Baker, Jr. Lou Baker is a Senior Chemist at the Argonne National Laboratory (ANL). He has an undergraduate degree in Chemical Engineering and a Ph.D. degree in Chemistry from the Illinois Institute of Technology. Before joining ANL, he was an aeronautical research scientist at the Lewis Laboratory of the National Advisory Committee for Aeronautics. At ANL, he has held a number of positions associated with reactor safety research. He was a group leader for investigations of metal-water and metal-air reactions throughout the 1960s. Later, he was Manager of the Safety Section of the liquid-metal fast breeder reactor (LMFBR) Program Office. Following that, he managed a research group studying postaccident heat removal for liquid metal reactors. He also served as a program manager in DOE's Technology Management Center for Fast Reactor Safety. He managed the concluding phase of the Electric Power Research Institute (EPRI)/Argonne Source Term Experiments Project (STEP). Currently, he is working with EPRI and Sandia National Laboratories (SNL) on the direct containment heating problem for light water reactors (LWRs).

Kenneth Bergeron is Supervisor of the Containment Modeling Division at SNL. This group is responsible for the development and application of the CONTAIN computer code, which is the USNRC's best-estimate, mechanistic analysis tool for severe accident containment analysis. Dr. Bergeron holds a Ph.D. degree in Physics from Brandeis University, where his dissertation work was in the area of theoretical non-equilibrium statistical mechanics. He has been at SNL for 14 years, where his research assignments before his current activities in reactor safety have ranged from theoretical studies of electrical breakdown of vacuum and insulators to systems analysis and economics of industrial solar energy. He has been associated with the

CONTAIN code for seven years, five of them as supervisor of the group working with this code. He was a member of the Containment Loads Working Group, and also participated in the expert panel assessments for the Draft NUREG-1150.

Theodore Ginsberg is Group Leader of the Experimental Modeling Group in the Department of Nuclear Energy at Brookhaven National Laboratory (BNL). He holds a Ph.D. and M.S. degrees in Nuclear Engineering from Pennsylvania State University and a Bachelor's degree in Chemical Engineering from Pratt Institute. His current research activities involve experimental and analytical modeling of multi-phase transport phenomena related to LWR nuclear safety. Severe accident research underway in his group currently involves the severe accident analysis issues of direct containment heating (DCH) and core-concrete interactions (CCIs) and aerosol release. He is presently directing research and developing models for characterizing transport phenomena occurring during DCH scenarios and is leading a plant-specific DCH containment loading analysis.

He began his career at ANL where he was Principal Investigator of a thermal-hydraulic project related to development of the LMFBR. While at ANL he also was involved in environmental studies related to thermal pollution of bodies of water by power plant condenser water outflow. He was a faculty member of The Technion - Israel Institute of Technology in Haifa, Israel, where his research included studies of the behavior of buoyant plumes, mathematical analysis of heat transfer in complex geometry and hydrodynamic mixing between connected parallel flow channels. Since 1974, his research activities have focused on many aspects of nuclear power plant safety. Related to his LMFBR analytical and experimental research, his published work includes studies of multi-phase heat and mass transfer in volume-heated boiling systems, application of microwave technology for simulation of the nuclear heat source, the impact of fluid instabilities on core disruptive accident energetics and convective solidification processes. He was involved in mathematical analysis of specific phenomenological issues and performed integrated analyses of LMFBR systems transients using large computer codes. More recently, he has been involved in a review of the Department of Energy's liquid-metal reactor (LMR) concept in the areas of probabilistic risk assessment and analysis of the new LMR metal fuels concept. His LWR research publications include experimental and analytical studies of multi-phase flow processes during the quench of packed beds of particles, aerosol generation resulting from sparging of liquid pools with gas bubbles, steam production during the quench of hot particulate falling through pools of water (steam spike) and condensation-induced water hammer. He has been involved in several technology assessments with published reports related to aspects of LWR, LMR and LMFBR phenomenology. He chaired the NRC's Steam Explosion Review Group and participated in the NRC's Containment Loads Working Group.

James Metcalf. No biographical sketch available.

Martin G. Plys. Martin Plys is the Manager of Methods Development at Fauske and Associates, Inc. (FAI). He is primarily responsible for development and application of the Modular Accident Analysis Program

(MAAP), the integrated accident analysis tool developed by FAI for the Industry Degraded Core Rulemaking (IDCOR) Program. His career has been devoted to reactor safety analysis, chiefly in research and model development for severe reactor accidents. He has extensive experience in integrated severe accident analyses covering all U.S. reactor types as well as several European reactors. His fields of research and expertise include CCIs and fission product release, hydrogen combustion, containment thermal-hydraulics, core melt progression, and fission product chemistry. Before joining FAI in 1984, he received an Sc.D. in Nuclear Engineering from Massachusetts Institute of Technology (MIT), and worked for Commonwealth Edison Company and Northern Indiana Public Service Company.

Martin Sherman. No biographical sketch available.

Patricia Worthington. No biographical sketch available.

Alfred Torri. Since 1990, Dr. Torri has been an independent consultant and the sole proprietor of Risk Safety Engineering. Dr. Torri holds Ph.D. and Masters degrees in Nuclear Engineering from MIT and a Bachelors degree in Mechanical Engineering from the Swiss Federal Institute of Technology. As an independent consultant, he was the principal investigator and technical lead for the Maine Yankee Level 2 PSA and the project manager and principal investigator for Mühleberg Level 2 PSA. His projects also included the documentation of the Mühleberg PSA Level 1 and 2 German main report and the IPE Level 2 containment event tree analysis for the Crystal River plant.

In the 1980s, while at Pickard, Lowe and Garrick, Inc. (PLG), he was a partner and the chairman of the PLG Technical Oversight Committee. He was responsible for methodology development and technical direction of containment response analysis (Level 2) on probabilistic risk assessment (PRA) projects. In this capacity, he was project leader and principal contributor for the Seabrook and Midland Level 2 PRAs, and project manager and principal investigator for the Beznau PRA (Level 1). He also managed and was the lead author on a project to document PLG PRA methodology and application, and he testified before the Advisory Committee of Reactor Safety and the Nuclear Regulatory Commission on reactor safety issues.

Earlier, as the manager of the Gas-Cooled Fast Reactor Program, Safety and Reliability Branch at General Atomic Company, he directed 6 to 12 engineers performing gas-cooled fast reactor safety assessments sponsored by the Department of Energy. At the MIT Research Reactor, he was the Senior Reactor Supervisor, overseeing all aspects of reactor operation, including startup, shutdown, refueling, maintenance, and testing. Throughout his career, Dr. Torri has been extremely active in professional organizations, such as the American Nuclear Society and the European Nuclear Society.

Molten Core/Containment Interaction Panel

David R. Bradley. David R. Bradley is a Member of Technical Staff at SNL. He holds a Ph.D. degree in Nuclear Engineering from the University of Virginia. Dr. Bradley has worked primarily on nuclear facility safety

problems and is an expert in the field of core debris interactions with concrete during severe accidents. Before joining SNL, he was an assistant professor at the University of Virginia where he conducted research in bubble behavior during hypothetical core disruptive accidents in LMFBRs. Since coming to SNL, he has been involved in experimental and analytical research on the interactions of molten and solidified core debris with concrete.

Michael L. Corradini. Michael Corradini is a professor in the Nuclear Engineering and Engineering Physics Department at the University of Wisconsin, Madison. He also holds a joint appointment in the Mechanical Engineering Department at the University and is the Director of the Nuclear Safety Research Center. He received his B.S. degree in Mechanical Engineering at Marquette University in 1975 and his M.S. and Ph.D. degrees in Nuclear Engineering at MIT in 1978. Before joining the university in 1981, he was a Member of Technical Staff at SNL, where he worked on severe accident research, particularly vapor explosion phenomena, molten core-concrete interactions and containment thermal-hydraulics. His current research activities are in the areas of nuclear reactor safety, particularly severe accidents (vapor explosions, molten core-concrete interactions, direct heating, containment thermal-hydraulics), radioactive waste management (transportation), fusion reactor technology (liquid metal/water interactions and liquid metal condensation), industrial safety (multi-phase multi-component flows) and combustion technology (spray dynamics). He is a consultant to the Advisory Committee on Reactor Safeguards (ACRS) sub-committees on Severe Accidents and Waste Management. He is also the university representative to the State Radioactive Waste Review Board's Technical Advisory Committee. He is a member of the American Nuclear Society (ANS), the American Society of Mechanical Engineers (ASME) and the American Institute of Chemical Engineers (AIChE).

George Greene. No biographical sketch available.

Michael J. Hazzan. Michael Hazzan is a Principal Nuclear Technology Engineer with Stone & Webster (S&W) Engineering Corporation in Cherry Hill, New Jersey. He has been a member of S&W's Source Term Project since 1982. He has participated in numerous severe accident thermal-hydraulics and fission product transport analyses of both PWRs and BWRs, including BWR analysis in support of Baltimore Gas and Electric's EP2 Reduction request for Calvert Cliffs, and an extensive analysis of containment bypass accidents in PWRs. He has performed these analyses with a variety of IDCOR, NRC and S&W codes. He has authored or co-authored a number of technical papers in the source term area or in emergency planning. He has also managed numerous safety-related jobs involving fault tree analysis, probabilistic risk analyses (PRAs), dispersion and consequence analysis for the chemical process industry. Before joining S&W, Mr. Hazzan spent seven years as a nuclear-trained naval officer.

Mujid S. Kazimi. Mujid S. Kazimi is a Professor of Nuclear Engineering at the MIT, Cambridge, Massachusetts with a B.S. degree from the University of

Alexandria, Egypt, 1969, and a Ph.D. degree in Nuclear Engineering from MIT, 1973. Before joining MIT, he worked at Westinghouse Advanced Reactor Division from 1973 to 1974 and BNL from 1974 to 1976. He has been interested in the heat transfer aspects of fission reactor design and safety, and in the implications of safety for fusion technology development. He has supervised over 40 graduate theses on fission and fusion reactor engineering. He has been a consultant to industry and several national laboratories on aspects of severe accidents in LWRs. He served on many Department of Energy (DOE) advisory committees, most recently the Senior Advisory Committee on Environmental, Safety and Economic Aspects of Magnetic Fusion Energy. He is a member and past chairman of the Nuclear Heat Transfer Committee of the AIChE and a current member of the executive committee of the thermal-hydraulic division of the ANS.

Bal Raj Sehgal. Dr Sehgal is a senior scientific advisor in the Nuclear Power Division at EPRI. He has a Ph.D. degree from the University of California at Berkeley. Before joining EPRI in 1974, he worked at BNL and ANL on problems in reactor physics, LWR analysis, fast reactor engineering, and safety. He served as a visiting professor at Purdue University (1973 to 1974), MIT (1980 to 1981), and University of California, Berkeley (1982 to 1983). At EPRI, he has managed programs in advanced reactors, code development and validation and is currently directing and performing research in the degraded core and source term areas. Dr. Sehgal is a Fellow of the ANS and is the executive editor of "Progress in Nuclear Energy", published by Pergamon Press.

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 where alternative sources of information such as experimental or observational data, or validated computer models are not available.
2. The issues analyzed using expert judgment should have the potential to make a significant impact on the estimates of risk and uncertainty in risk.
3. The decomposition of complex issues into simpler assessments is made in order to improve the quality of the resulting information.
4. Issues should be presented to the experts without ambiguity and without the potential for preconditioning or biasing responses.
5. Experts should be trained in the practice of expressing knowledge and beliefs as probability distributions.
6. Discussion of issues and alternative beliefs should take place in structured and controlled meetings that encourage the exploration of alternative beliefs while inhibiting pressure to conform.
7. Elicitation of expert opinion should be conducted using techniques and instruments that reflect the state of the art in subjective probability assessment.
8. The aggregation of judgments from various experts should preserve the uncertainty that exists among alternative points of view. Equal weight should be assigned to the assessment for each expert to represent the uncertainty completely.

NUREG-1150 does not attempt to reduce uncertainty in risk analysis, nor is it an attempt to find a best estimate. This study is an attempt to produce an unbiased picture of uncertainty in risk. The study tries to discover the range in risk inherent in the range of plausible assumptions about phenomenology and initial and boundary conditions. The risk corresponding to the most (subjectively) plausible assumptions has a higher likelihood of being accepted by a randomly chosen expert in accident phenomena. The risk

corresponding to less plausible assumptions nevertheless has some likelihood of being accepted by any expert, and may indeed be the most acceptable for some experts. Experts are sometimes wrong, and the "true" risk could lie outside the ranges found in this study.

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 due to 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:

- High impact on risk. 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

<u>Issue No.</u>	<u>Title</u>	<u>Reason for Inclusion</u>
1	Temperature-induced PWR hot leg failure	Large hot leg failure could preclude direct containment heating; depressurizes RCS and precludes steam generator 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 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

<u>Issue No.</u>	<u>Title</u>	<u>Reason for Inclusion</u>
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 Molten Core-Containment Interaction Panel

<u>Issue No.</u>	<u>Title</u>	<u>Reason for Inclusion</u>
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 3-4
Issues Presented to the Structural Response Panel

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

Table 3-5
Issues Presented to the Source Term Panel

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

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 has been 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 both the Containment Loads and Molten Core/Containment Interaction Expert Panels was Professor Detlof von Winterfeldt of the University of Southern California.

The purpose of training in probability assessment is to facilitate the elicitation process. Experts in various fields of science are often not trained in probability theory and the techniques of probability elicitation. The expertise possessed by the scientists and engineers on the panels is called substantive expertise. 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, 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. Furthermore, 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 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 twofold: 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 includes 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. A list of references that were provided to relevant panel is presented in Appendix I.

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 which 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 analyst 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 or the XSOR codes. 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 accident progression 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, that 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 used 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 dependant 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 used 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 was 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 which

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 analysts. 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.

REFERENCES

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4. ELICITATION MEETINGS

The first two meetings (the elicitation training and the presentation and review of the technical issues) for both the Containment Loads Expert Panel and the Molten Core/Containment Interaction (MCCI) Expert Panel were held on December 15 to 17, 1987. Presentations to the Containment Loads Panel were made by the following people:

Nestor Ortiz, SNL
Detlof von Winterfeldt, USC
Frederick Harper, SNL
Eric Haskin, SNL
Chris Amos, SAIC
Martin Sherman, SNL
Martin Plys, FAI
Julie Gregory, SNL
Arthur Payne, SNL
Susan Dingman, SNL
Marshall Berman, SNL
Walter Murfin, Technadyne
William Tarbell, SNL
Theodore Ginsberg, BNL
David Williams, SNL

Presentations to the MCCI Expert Panel were made by the following people:

Nestor Ortiz, SNL
Detlof von Winterfeldt, USC
Frederick Harper, SNL
Eric Haskin, SNL
Chris Amos, SAIC
Ervin Copus, SNL
Arthur Payne, SNL
George Greene, BNL
Martin Plys, FAI
Jay Weingardt, SAIC
Dana Powers, SNL

The elicitation meeting for the MCCI Expert Panel was held on March 1 to 3, 1988. Presentations were made by the following people:

Frederick Harper, SNL
Ralph Keeney, USC
Kenneth Bergeron, SNL
Jay Weingardt, SAIC
Roger Breeding, SNL
Elaine Bergeron, SNL
Dave Bradley, SNL
Mike Corradini, U of W
George Greene, BNL
Mujid Kazimi, MIT
Raj Sehgal, EPRI
Mike Hazzan, S&W
Arthur Payne, SNL

The Containment Loads Expert Panel held an additional meeting between the first two meetings and the elicitation meeting. This meeting was held independently of the NUREG-1150 project staff. The elicitation meeting for the Containment Loads Expert Panel was held on March 8 to 11, 1988. Presentations were made by the following people:

Elaine Gorham, SNL
Ralph Keeney, USC
Roger Breeding, SNL
Chris Amos, SAIC
Thomas Brown, SNL
Jim Marcalf, S&W
Louis Baker, ANL
Martin Sherman, SNL
Julie Gregory, SNL
Patricia Worthington, NRC
Arthur Payne, SNL
Marty Plys, FAI
Alfred Torri, PL&G
Kenneth Bergeron, SNL
Kenneth Murata, SNL
Theodore Ginsberg, BNL
Walter Murfin, Technadyne

Normative experts for both Containment Loads and MCCI elicitation sessions were:

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

5. CONTAINMENT LOADS ISSUES RESULTS--Part 1

This section presents the results of the expert panel elicitations on Containment Loads issues. Each subsection contains a brief description of each issue, the individual expert assessments and rationale for the assessments, and the aggregated results or resolutions for each issue.

During the elicitations, many of the experts preferred to think in terms of number of occurrences of an event over number of trials (or in terms of the frequency of an event). Because this document presents the information received from the Containment Loads and Molten Core/Containment Interaction Expert Panels and attempts to represent their thought process accurately, many of the parameters discussed in this document are discussed as frequencies (such as the frequency of hydrogen ignition). However, the values that were provided by the experts were always converted to conditional probabilities for use in the accident progression event trees.

5.1 Containment Loads Issue 1. Hydrogen Phenomena at Grand Gulf

Summary of Expert Panel's Assessment of Issue 1: Hydrogen Phenomena at Grand Gulf

Experts consulted: Louis Baker, Argonne National Laboratory; James Metcalf, Stone & Webster; and Martin Sherman, Sandia National Laboratories.

Issue Description

There are three parts to this issue. Each part is presented below as a question.

Part 1. What distributions characterize the uncertainty in the probability that hydrogen combustion occurs in the containment (wetwell)?

Two cases are considered:

1. Station blackout with loss of all dc power. The reactor pressure vessel (RPV) remains at high pressure during core damage since loss of dc power precludes depressurization.
2. Short-term station blackout with dc power available. The RPV is depressurized before core damage.

Part 2. What distributions characterize the uncertainty in the probability that hydrogen combustion occurs in the containment at Grand Gulf when RPV breach occurs at high pressure?

Part 3. Given that hydrogen combustion occurs in the containment, what distributions characterize: the peak static pressure attained in the containment; the maximum impulse loading to the drywell wall; and the completeness of combustion?

Three cases are considered:

1. Steam partial pressure is 50 kPa, air partial pressure is 115 kPa, and containment sprays are not operating. Ignition occurs without recovery of ac power.
2. Steam partial pressure is 50 kPa, air partial pressure is 115 kPa, and containment sprays initiate approximately 90 s after ignition occurs (assume to result from ac power recovery).
3. Steam partial pressure is 135 kPa, air partial pressure is 120 kPa, and containment sprays initiate 90 s after an ignition source is introduced (assumed to result from ac power recovery).

For all parts of this issue, other cases are possible. The review panels were given only those cases that were assessed to have the greatest risk significance based on the experience of the analyst.

Summary of Experts' Rationale

Part 1

Expert A felt that the uncertainty associated with this issue is dominated by the uncertainty in ignition. For ignition to occur, the hydrogen in the containment must be in the flammable range and a spark must occur. If ignition sources are present, the frequency of ignition depends on the hydrogen concentration and the amount of time spent at a given hydrogen concentration. However, for each case the Expert felt that there was some probability that there are no ignition sources. The Expert expressed the ignition frequency in terms of a "half-life" defined as the amount of time until the frequency of ignition equals 0.5. The "half-lives" were considered functions of hydrogen concentration. The primary difference between Cases 1 and 2 is the manner in which the hydrogen is released from the vessel into the containment. The ignition frequency is greater in Case 1 than in Case 2. There are two reasons for this difference. First, in Case 1 local "pockets" of hydrogen concentration can form above the suppression pool and can have a hydrogen concentration higher than the rest of the containment atmosphere. Second, the likelihood of generating a static spark is greater for Case 1 than for Case 2 because of the high SRV tailpipe discharge gas velocities associated with the former.

Part 2

The Expert felt the probability of ignition at vessel breach depended on the likelihood that hot debris or hot gases from the drywell enter the containment. The Expert indicated that if hot debris ($> 500^{\circ}\text{C}$) enters the containment, and the hydrogen concentration is in the flammable range ($>5\% \text{H}_2$), the hydrogen will ignite. The Expert felt that if the hydrogen in the drywell at vessel breach (or that which is released from the RPV at vessel breach) ignites, the gases and debris in the drywell will be hot enough to ignite a combustible atmosphere. However, cooling of the hot gases and debris in the suppression pool will reduce the probability of ignition.

Part 3

For static loads, Expert A based his assessment on the adiabatic isochoric complete combustion (AICC) model. The resulting peak pressure rise was then modified to account for burn completeness, pressure relaxation from vent clearing, and heat transfer to structures. Burn completeness was considered a function of hydrogen concentration and containment atmosphere turbulence. (If the containment sprays were operating, the atmosphere would be turbulent.) It was felt that incomplete combustion would occur at containment hydrogen concentrations below 12%. For burn completeness, the Expert used empirical correlations developed by Wong.^{A-1} The Expert indicated that should the gas expand into the drywell, due to deflagrations in the wetwell causing the suppression pool surface to lower, the peak deflagration pressure would be reduced by approximately 10%. Referencing Cummings,^{A-2} the Expert felt that the reduction in pressure due to the heat transfer to structures would be on the order of 10%. Combining all this, the peak overpressure was expected to be on the order of 20% lower than that predicted by the AICC model.

For Case 3, the Expert cites flammability limit studies which show incomplete burning in regions just inside the flammability limits. He concluded that if the inert mixture is slowly brought into the flammable range, it must cross a region of weakly flammable mixtures where deflagrations will have low pressure rises because of incomplete combustion. The Expert believed overpressures for this case would be negligible.

The Expert felt that the likelihood that a detonation will occur in a region, given that ignition has occurred, depends on the geometry of the region and the hydrogen concentration at ignition. The methodology of Sherman and Berman,^{A-3} where the hydrogen-air-steam mixture and the containment geometry are classified on a scale, was used to determine the likelihood of detonation. It was felt that detonations in the dome area are highly unlikely, and only detonations in the annulus region were considered.

For Case 3, the scenario assumes that an initially steam inert hydrogen-air-steam environment is slowly brought into a flammable range by the condensation of steam caused by sprays. The cooling of the containment atmosphere is slow and ignition sources are present. The Expert referenced the work of Sherman and Slezak^{A-4} that shows that for hydrogen-air-steam mixtures in large geometries the detonation limits lie inside the flammability limits. A region of "weakly flammable mixtures" is defined through which any inertly mixture must pass before reaching the "strongly flammable and possibly detonable region." Thus, the Expert believes the probability of a detonation is zero.

Given that a detonation occurs, the Expert felt that reverberations could increase the maximum impulse from the first impulse. He indicated that it was most likely that the impulse on the drywell would be twice that of the first impulse.

Part 1

Expert B based his uncertainty distributions on his experience with hydrogen combustion phenomena. He noted that experimental results suggest that ignition probabilities increase as the molar concentration of hydrogen increases. The Expert felt that because the steam mole fraction is large, there is a low probability of ignition from random discharges of static electricity. He also accepted the belief of the NUREG-1150 analysts that the presence of dc power in Case 2 did not constitute a clear ignition source. The other difference in containment volume conditions between Cases 1 and 2 is that for Case 1 the hydrogen release occurs through a single SRV, while for Case 2 it occurs through all automatic depressurization system (ADS) valves and is far more distributed. Expert B stated that the hydrogen would mix well with the containment atmosphere and no distinction is made between Cases 1 and 2 for this part of the issue.

When the Expert had selected a best-estimate ignition probability for each selected hydrogen concentration, a beta distribution was selected which approximately represented his judgment as to the uncertainty in that assessment.

Part 2

Expert B based his assessment on an assumed likelihood for hot gas from the drywell to enter the containment at vessel breach. He believed that the level in the suppression pool would be severely depressed before vessel breach. Given the short distance between the level of the suppression pool and the top row of vents, the Expert felt that it is likely that hot gas could flow from the drywell into the wetwell without equilibrating with the pool water. He felt that it is unlikely that hot debris could pass into the wetwell; however, the hot gas might be sufficient for an ignition. Given that steam exiting the vessel could be heated by ejected debris near the top of the weir wall, the resulting local temperatures could be sufficiently high to result in ignition. Since some cooling by the pool would occur, ignition is less than certain.

The Expert felt that the ignition probability and the uncertainty in the ignition probability increase with increasing hydrogen concentration. The principal uncertainty stems from whether an ignition source is present or not. The same procedure for assessment was used as in Part 1.

Part 3

Expert B based his assessment on the adiabatic pressure resulting from combustion of a given molar concentration of hydrogen. This maximum pressure was modified based on his judgment about the likely completeness of the burn. Detonation was assessed to be impossible below a hydrogen mole fraction of 16%.

The Expert based his assessment of burn completeness on: (a) research results that compare peaks obtained during combustion experiments at various burn facilities with the corresponding AICC pressures; (b)

discussions with other panel members; and (c) his knowledge of hydrogen phenomena. Again, a beta distribution was chosen to reflect Expert B's judgment about the uncertainty in burn completeness. The completeness of burn was thought to increase with increasing hydrogen concentration.

Expert B believed that Cases 1 and 2 for this part would behave identically, as the sprays are initiated too late in Case 2 to impact the peak pressure attained. For Case 3, he felt that the pressure attained would be reduced because the burn was slower, but the burn completeness would remain the same as for the low-steam Cases 1 and 2 for a given hydrogen concentration.

Expert B based his assessment of dynamic loads largely on the work presented by Expert A. Following that Expert, he stated that a detonation would produce a load that was independent of the hydrogen concentration at which ignition occurred. He felt that there was little uncertainty in the load induced. However, the probability of a detonation occurring was seen to be strongly dependent on the presence of a minimum hydrogen concentration.

Expert C analyzed the problem by subdividing the three initial cases into three subcases each on the basis of percent of cladding and percent of channel boxes reacting. For release before vessel failure, he constructed a CDF for average concentration based on the results of computer code runs for each of the cases. A CDF was then constructed for peak concentration using his judgment about the effects of nodalization and mixing on the realistic peak concentrations expected. Then the probability of ignition vs. peak concentration was assessed with uncertainty bounds. The split fraction for the resulting combustion being a diffusion flame, a deflagration or a detonation vs. peak concentration level was assessed. Next, the peak pressure or impulse vs. peak concentration was found.

Method of Aggregation

Assumptions Used To Average Distributions

Levels of hydrogen concentration were used to represent the continuous range of possible hydrogen concentrations. Five levels of H_2 concentration were used for the assessments of ignition frequency. The five levels were 0 to 4% H_2 , 4 to 8% H_2 , 8 to 12% H_2 , 12 to 16% H_2 , and greater than 16% H_2 . If the Expert's distribution corresponded to a particular hydrogen concentration, the level was characterized by the midpoint of the interval (e.g., 6% characterizes the interval from 4 to 8% H_2). For the assessment of detonation frequency for the low steam case two levels of hydrogen concentration were used, 16 to 20% H_2 and greater than 20% H_2 . For the high steam case, detonation frequencies were obtained for hydrogen concentrations in the following two intervals, 12 to 16% H_2 and 16 to 20% H_2 .

Assumptions Applied to Expert A's Distributions. This Expert felt that the frequency of ignition was a random event and could be represented by a

"half-life" model. The method and assumptions used to convert the "half-life" model into a cumulative distribution function for the five hydrogen levels are described in the individual expert elicitation write-up for this issue.

For the burn completeness the Expert gave values for both turbulent (sprays on) and static (sprays off) conditions in the atmosphere. The difference in burn completeness for these two sets of conditions is small and the effect it has on the overpressure is equally small. Therefore, the burn completeness factors for turbulent and static conditions were averaged together to get an overall set of burn completeness factors.

Assumptions Applied to Expert B's Distributions. The Expert gave distributions for ignition frequency, detonation frequency, and burn completeness at discrete hydrogen concentrations. To obtain distributions in the interval between the assessed distributions, the mode and spread factor for the new distribution were obtained by linear interpolation of the values at the endpoints of the interval.

The static overpressure was determined by subtracting the initial pressure in the containment from the adiabatic isochoric complete combustion (AICC) pressure and then multiplying the result by the burn completeness.

Assumptions Applied to Expert C's Distributions. The Expert typically represented his uncertainty in a parameter by providing the value of the parameter at the 5%, 50%, and 95% fractiles. It was assumed that a straight line could be used to connect any two consecutive points. Parameter values at the 0% and 100% fractile level were obtained by linear extrapolation of the two closest points (e.g., for 0% the values at 5% and 50% were used).

When assessing the peak pressure, which results from a diffusion burn or a deflagration, the Expert assumed an initial containment pressure. However, this pressure is different than the initial pressures which correspond to the various cases for this issue. To convert the peak pressure to the correct initial pressure, the initial pressure assumed by the Expert was subtracted from the peak pressure. The initial pressure, appropriate for the case under consideration, was then added to the resulting pressure difference.

The Expert provided the peak pressure for both a diffusion burn and a deflagration. In order to reduce the number of cases that must be considered, the peak pressure caused by a diffusion burn was averaged with the peak pressure caused by a deflagration. The Expert assessed the likelihood of a diffusion burn and the likelihood of a deflagration. This split fraction was used to "weight" the two peak pressure during the averaging process.

For case 1b/2b (Expert's case structure) the Expert indicated that a detonation could occur in the interval from 12% to 16% H_2 . However, the impulse from this detonation is approximately 1 kPa-s, which is a very minor impulse in terms of its threat to the integrity of the drywell or the

containment. Thus, this level was not included in the aggregation process for detonations. Similarly, for case 3b the Expert indicated that a detonation could occur in the interval from 8% to 12% H_2 . Again, the impulse resulting from a detonation in this interval will be minor and, therefore, this level was also not included in the aggregations process for detonations.

For case 1b/2b, the impulses from detonations were assessed for the following two levels: 16% to 20% H_2 and greater than 20% H_2 . For case 3b the impulses from detonations were also assessed for two levels of hydrogen concentration. The two levels are 12% to 16% H_2 and 16% to 20% H_2 . In order to present these results in a format similar to the other two experts and to reduce the number of cases that needed to be considered, the two impulse distributions associated with each case (cases 1b/2b and 3b) were averaged together. The result is a unique impulse distribution for each case which is no longer a function of hydrogen concentration.

Aggregated Results

The plots on the following pages show the aggregated results of all the experts.

Figure S-1. Ignition Before Vessel Breach; RPV at Low Pressure.

Figure 5-2. Ignition Before Vessel Breach; RPV at High Pressure.

Figure 5-3. Ignition At Vessel Breach; RPV at High Pressure.

Figure 5-4. Hydrogen Burn Completeness.

Figure 5-5. Deflagration Over Pressure; Wetwell; Low Steam.

Figure 5-6. Deflagration Over Pressure; Wetwell: High Steam.

Figure 5-7. Probability of Detonation--Low Steam.

Figure 5-8. Probability of Detonation--High Steam.

Figure 5-9. Loads From Hydrogen Detonation in Wetwell.

Individual Elicitations for Issue 1

Expert A's Elicitation

Issue 1. Hydrogen Phenomenon at Grand Gulf

Part 1

Description of Expert A's Rationale/Methodology

The Expert felt that the uncertainty associated with this issue was dominated by the uncertainty in ignition. The model used by the Expert for ignition is as follows.

The hydrogen concentration in the containment must be in the flammable range ($\% \text{ hydrogen} > 5\%$) and a spark must occur. For each case there is a certain probability that there are no ignition sources (i.e., no sparks). If there are ignition sources, the frequency of ignition depends on both the hydrogen concentration and the amount of time spent at a given hydrogen concentration. That is, the occurrence of a spark from an ignition source is a random process. The Expert expressed the ignition frequency in terms of a "half-life" (meaning the amount of time until the frequency of ignition equals 0.5). The Expert considered the "half-lives" as a function of hydrogen concentration. The primary difference between Cases 1 and 2 stem from the way the hydrogen is released from the vessel into the containment. For case 1 (reactor pressure vessel [RPV] is at high pressure) the hydrogen is periodically released through one safety relief valve (SRV) tailpipe and, therefore, local "pockets" of hydrogen form which have hydrogen concentrations higher than the mean hydrogen concentration in the containment. For Case 2 (RPV is at low pressure), the hydrogen is released uniformly in the suppression pool and the size of hydrogen "pockets" are reduced accordingly. In addition, the chance of generating a static spark is greater for Case 1 than for Case 2 because of the high gas velocities (gas being released through one SRV tailpipe as opposed to several tailpipes) associated with the former.

Results of Expert's A's Elicitation

The ignition frequencies, expressed as "half-lives," are presented in Table A-1 as a function of local hydrogen mole percent in the containment. For Case 1, the Expert indicated that the local hydrogen concentration is about 4% greater than the mean hydrogen concentration. Similarly, for Case 2, the local hydrogen concentration is about 2% greater than the mean hydrogen concentration. The local hydrogen concentrations are greater than the mean hydrogen concentrations because of local "pockets" of hydrogen that are formed when the hydrogen is released from the SRV tailpipes. The Expert also felt that for the low steam cases (20 to 30% steam) the probability of no ignition sources being present was 0.25.

Table A-1
Hydrogen Ignition Half-Lives

Local H ₂ Concentration (Mole Fraction)	Half-Life (min)
0.05 to 0.10	25.0
0.10 to 0.15	15.0
0.15 to 0.20	10.0
0.20 to 0.40	5.0
0.40 to 0.60	10.0

The ignition frequencies, when expressed with "half-lives," are a function of both time and hydrogen concentration. What is desired is a CDF for the frequency of ignition for several ranges of hydrogen concentration. To generate this CDF the amount of time the hydrogen could be in the containment before vessel breach must be specified. Based on results from MELCOR and BURSAR code calculations it was estimated that the time interval from the start of significant hydrogen production to vessel breach was 2 h. In addition, because most of the hydrogen is produced over a relatively short period of time, it was assumed that the total amount of hydrogen generated was released to the containment at the beginning of the 2-h interval. It was then assumed that any time within this time interval was equally interesting and a CDF for the frequency of ignition was generated for a given hydrogen concentration range. Five containment hydrogen concentration (mole percent) ranges were selected: 0.0 to 4.0%, 4.0 to 8.0%, 8.0 to 12%, 12 to 16%, and greater than 16%. The resulting distributions for cases 1 and 2 are presented in Figures A-1 and A-2, respectively.

A short explanation of the terminology used in these two figures is needed. For a stochastic event the term "frequency" is used to describe the fraction of times a particular outcome occurs, if the event were repeated a large number of times. However, the actual value for this frequency may be uncertain. The term probability is used to describe this uncertainty. Associated with each frequency in Figures A-1 and A-2 is a probability which represents the likelihood that the actual frequency does not exceed this value.

Sources of Uncertainty

The Expert indicated that the major source of uncertainty was the lack of identifiable ignition sources. In addition, the Expert also cited the lack of experimental results which also led to the large amount of uncertainty.

Figure A-1. Ignition Frequency Before Vessel Breach Short-Term Station Blackout, High Pressure for Case 1

Figure A-2. Ignition Frequency Before Vessel Breach Short-Term Station Blackout, High Pressure for Case 2

Part 2

Description of Expert A's Rationale/Methodology

The Expert felt the probability of ignition at vessel breach depended on the likelihood that hot debris or hot gases from the drywell would enter the containment. The Expert indicated that if hot debris ($> 500^{\circ}\text{C}$) enters the containment and the hydrogen concentration is in the flammable range ($> 5\% \text{ H}_2$), the hydrogen will ignite. The Expert felt that if the hydrogen in the drywell at vessel breach (or that which is released from the RPV at vessel breach) ignites, hot gases and debris with sufficient energy to ignite the hydrogen in the containment will exist in the drywell. (The energy released from this hydrogen burn will heat the gases in the drywell and will tend to keep the debris particles hot, which increases the likelihood that hot debris particles and gases will enter the wetwell.) However, cooling of the hot gases and debris in the suppression pool will reduce the probability of ignition. It is also possible that the debris will be blanketed by steam as it enters the containment, which will also reduce the probability of ignition.

Results of Expert A's Elicitation

The Expert believed that if the hydrogen in the drywell at vessel breach (or that which is released from the RPV at vessel breach) ignites, the probability of ignition in the wetwell is 0.67. However, he assigned a probability 0.1 that there would be no hydrogen ignition in the drywell (insufficient amount of oxygen or too much steam). Thus the overall probability of ignition at vessel breach in the wetwell is 0.6.

Sources of Uncertainty

The Expert cited the interaction of the pool with the hot debris as a major source of uncertainty. The uncertainty in the amount of vent coverage and the possibility of gas blow-through also contributed to the overall uncertainty associated with this parameter. If, however, hot debris entered the wetwell and a flammable mixture was present, he was certain it would ignite.

Part 3

Description of Expert A's Rationale/Methodology

Static Load

For static loads the Expert based his assessment on the adiabatic isochoric complete combustion (AICC) model. He then modified the peak pressure rise obtained from this model to account for burn completeness, pressure relaxation from vent clearing, and heat transfer to structures. The Expert expressed the burn completeness as a function of both hydrogen concentration (mole fraction) and containment atmosphere turbulence. If the con-

tainment sprays were operating, the Expert indicated that the atmosphere would be turbulent; otherwise, it would be quiescent. The Expert felt incomplete combustion would occur at containment hydrogen concentrations (average) below 12%. For burn completeness, the Expert used the empirical correlations developed by Wong.^{A-1} The Expert indicated that deflagrations in the wetwell will cause the suppression pool surface to move downward, and if it moves downward fast enough to uncover the top vent openings, the gas can expand into the drywell. The Expert estimated that the effect of gas expansion into the drywell would reduce the peak deflagration pressure by approximately 10%. The final reason for getting deflagration pressures below AICC is heat transfer from the burned gases to solid surfaces. To estimate the effects of heat transfer, the Expert referenced Figure 2.125 of Cummings,^{A-2} which indicates that typical pressure reductions are on the order of 5 to 10%. For pressure reduction due to heat transfer to structures, the Expert assumed a value of 10%. Therefore, the Expert stated that the peak overpressure can be expected to be of the order of 20% lower than AICC due to heat transfer to solid surfaces and expansion of wetwell gases into the drywell.

For Case 3, the scenario assumes that an initially steam inert hydrogen-air-steam environment is slowly brought into a flammable range by the condensation of steam caused by sprays. For this case the cooling of the containment atmosphere is slow and ignition sources are present. The Expert cites flammability limit studies which have shown incomplete burning in regions just inside the flammability limits. Therefore, he concludes that if an inerted mixture is slowly brought into the flammable range, it must cross a region of weakly flammable mixtures, a region where deflagrations will have low pressure rises because of incomplete combustion. The Expert believed overpressures for this case would be negligible.

Detonation Loads

The Expert stated that the likelihood that a detonation will occur, given that ignition has occurred, depends on the geometry of the region in which the detonation may occur and on the hydrogen concentration at ignition. The Expert used the methodology of Sherman and Berman^{A-3} to determine the likelihood of a detonation. This methodology requires that both the hydrogen-air-steam mixture and the containment geometry be classified on a scale from 1 to 5 where a class of 1 indicates a condition conducive for a detonation. The Expert divided the Grand Gulf containment into two regions: the annulus region of the wetwell and the dome region of the upper containment. The Expert felt the annulus region would be geometric class 2, geometries which favor flame acceleration but are not ideal for flame acceleration. Because of the large open area of the dome region, the Expert felt this region would be class 4, geometries unfavorable to flame acceleration. In addition, the Expert felt that it was unlikely that the hydrogen would ignite in the dome region (lack of ignition sources). Thus, the Expert concluded that the probability of a detonation in the dome region was very small and, therefore, dropped this region from his analysis. The Expert indicated, however, that a more complete method of analysis would involve assessing the likelihood of ignition in each region.

If the hydrogen ignites in the annulus region, there is a certain probability that it will detonate in this region. If the hydrogen does not detonate in the annulus region, it is possible that the flame will propagate into the dome region and detonate. Similar logic would be used for ignitions that originate in the dome region. But again, because detonations in the dome region were considered to be very unlikely, only detonations in the annulus region were considered. The mixture class is determined from Table 1 and Figure 3 of Reference 3. The Expert assumed the strongly flammable region, where dangerous flame acceleration or deflagration-to-detonation transition (DDT) is possible, is bounded by mixtures with a detonation cell width equal to 10 m. Figure 5 of Reference 4 is used to determine the hydrogen/steam region in which a detonation will not occur. Table 2 of Reference 3 is used to collapse the mixture class and the geometry class into a results class. Based on this methodology, the possible results classes that are possible for cases 1 and 2 are: Class 3, DDT may occur; Class 4, DDT is possible but unlikely; and Class 5, DDT is highly unlikely to impossible. The Expert then assigned a probability of detonation to the various results classes.

For Case 3, the scenario assumes that an initially steam inert hydrogen-air-steam environment is slowly brought into a flammable range by the condensation of steam caused by sprays. For this case the cooling of the containment atmosphere is slow and ignition sources are present. The Expert referenced work performed by Sherman and Slezak^{4,4} which showed that for hydrogen-air-steam mixtures in large geometries the detonation limits lie inside the flammability limits. Sherman and Slezak define a region of "weakly flammable mixtures" between the flammability limits and the detonation limits in which a DDT or highly accelerated flame cannot occur. The Expert stated that any inerted mixture must pass through this region before it gets to the "strongly flammable and possibly detonable region." Thus, based on this work the Expert believes the probability of a detonation is zero.

Given that a detonation occurs, the Expert estimated the magnitude of the impulse on the drywell wall from the detonation. The Expert indicated that if the first impulse is the peak impulse, then the impulse should be in the range from 6 to 24 kPa-s. However, the Expert felt that reverberations could increase the maximum impulse. He indicated that it was most likely that the impulse on the drywell would be twice that of the first impulse (first impulse plus the integrated effect of the remaining impulses).

Results of Expert's A's Elicitation

Static Loads

The burn completeness for Cases 1 and 2 are presented in Table A-2 as a function of containment hydrogen mole fraction. When the sprays are "on", the burn completeness factors for the turbulent case are used; otherwise, the static burn completeness factors are used.

Table A-2
Hydrogen Burn Completeness

<u>Average Wetwell H₂</u> <u>Mole Fraction</u>	<u>Burn Completeness</u>	
	<u>Static</u>	<u>Turbulent</u>
0.20	1.00	1.00
0.15	1.00	1.00
0.12	1.00	1.00
0.10	0.87	0.90
0.08	0.57	0.62
0.06	0.27	0.33
0.04	0.00	0.05

An AICC was used to obtain the containment overpressure as a function of hydrogen concentration. The burn completeness factors were used to determine the amount of hydrogen that should be burned (e.g., if the burn completeness is 50%, then 50% of the hydrogen is burned). To obtain the peak overpressure, the AICC pressure was multiplied by 0.8. Reducing the AICC pressure by 20% accounts for pressure relaxation due to heat transfer to solid surfaces and expansion of wetwell gases into the drywell. For Cases 1 and 2, the peak overpressure, as a function of containment hydrogen concentration, is presented in Figure A-3. For Case 3 the peak overpressure is negligible.

Detonation Loads

The probability of a detonation, given that ignition has occurred, is dependent on the results class. The Expert used the methodology of Sherman and Berman^{A-3} to determine the results classes as a function of containment hydrogen concentration. The results class is dependent on the geometry class and the hydrogen-air-steam mixture class. The Expert stated that the most probable location for a detonation was in the annulus region of the wetwell. This region was classified as a geometry class 2. The Expert assigned a probability of detonation to each results class. The probabilities of detonation for the three results classes are presented in Table A-3. The detonation probability for the annulus region of the wetwell is presented in Figure A-4.

Table A-3
Detonation Probability

<u>Results Class</u>	<u>Detonation Probability</u>
3	0.50
4	0.20
5	0.05

Figure A-3. Deflagration Overpressure (Wetwell) Low Steam Case.

Figure A-4. Frequency of Detonation at Grand Gulf Low Steam Case.

Given that a detonation occurs and the first impulse is the peak impulse, the Expert assigned a 90% probability that the peak impulse will be between 6 kPa-s and 24 kPa-s. However, the Expert estimated that the likelihood that a subsequent impulse will be greater than the first impulse to be 65%. The relative likelihood that subsequent peaks will be the maximum impulse are presented in Table A-4. The composite cumulative probability distribution for impulse to the drywell from a detonation is presented in Figure A-5.

Table A-4
Relative Likelihood Subsequent Peaks are Maximum Impulse

<u>Maximum Impulse</u> (kPa-s)	<u>Relative Likelihood</u>
12	1.0
24	1.5
36	1.0
48	0.4
60	0.1

Sources of Uncertainty

Static Loads

The Expert believes the uncertainty associated with the ignition frequency overshadows the uncertainty associated with the pressure rise from a hydrogen burn. Thus, the Expert did not assign any uncertainty to the parameters involved with static loads (i.e., burn completeness or overpressure).

Detonation Loads

Uncertainty in the location of the detonation and the potential of geometry for flame acceleration contributed to the uncertainty in the likelihood of a detonation. In addition, the Expert indicated that the uncertainty in the location of the detonation contributed to the uncertainty in the impulse load. The Expert felt that interactions between the detonation wave and the structures could significantly affect the peak impulse.

Figure A-5. Loads From Hydrogen Detonation in Grand Gulf Wetwell.

REFERENCES

- A-1. C. C. Wong, "HECTR Analyses of the Nevada Test Site (NTS) Premixed Combustion Experiments," Sandia National Laboratories, NUREG/CR-4916, SAND87-0956, November 1988.
- A-2. J. G. Cummings et al., "Review of the Grand Gulf Hydrogen Igniter System," Sandia National Laboratories, NUREG/CR-2530, SAND82-0218, February 1983.
- A-3. M. P. Sherman and M. Berman, "The Possibility of Local Detonations During Degraded-Core Accidents in the Bellefonte Nuclear Power Plant," Sandia National Laboratories, NUREG/CR-4803, SAND86-1180, January 1987.
- A-4. M. P. Sherman and S. E. Slezak, "Hydrogen-Air-Steam Combustion Regimes in Large Volumes," in Proceedings of the Twenty-Fifth Space Congress, Cocoa Beach, Florida, April 1988.

Expert B's Elicitation

Issue 1. Hydrogen Phenomenon at Grand Gulf

Part 1

Description of the Expert B's Rationale/Methodology

Expert B based his uncertainty distributions on his experience with hydrogen combustion phenomena. He noted that experimental results suggest that ignition probabilities increase as the molar concentration of hydrogen increases. Furthermore, Expert B felt that uncertainty in the probability that ignition would occur increases as the hydrogen concentration increases.

Because the steam mole fraction in the containment is large, (in this Expert's opinion a 0.2 steam mole fraction is large), low probability of ignition was expected from random discharges of static electricity. In the presentation of the Grand Gulf plant design, it was stated that the NUREG-1150 analysts believe that the presence of dc power in Case 2 did not constitute a clear ignition source. Expert B accepted this conclusion, since he had no other sources of information. The only other difference between Cases 1 and 2, in terms of conditions in the containment volume, is that hydrogen release for Case 1 occurs through a single SRV and thus the hydrogen enters the containment through the suppression pool over a limited area. (The surface area of the pool through which hydrogen bubbled would be no greater than one-eighth of the total surface.) For Case 2, all automatic depressurization system (ADS) valves are assumed to be open and thus the hydrogen source is far more distributed. Expert B stated that based on his knowledge of hydrogen behavior and comments about experimental results from one of the other panel members, the hydrogen would mix well with the containment atmosphere. No distinction is made between Cases 1 and 2 for this part of the issue.

Results of Expert B's Elicitation

Expert B gave his results in terms of the best-guess probability (interpreted as the mode of a distribution) of ignition for a given hydrogen concentration. The range of possible hydrogen concentrations was represented by five discrete points. Expert B stated that a 4% or lower molar concentration of hydrogen could not ignite. The lower end of the range is thus 4% hydrogen with the probability of ignition taken as zero with no uncertainty. Above a 20% molar concentration of hydrogen, Expert B stated that the probability of ignition was independent of further increases in concentration. Thus, 20% hydrogen concentration was taken as the upper end of the range. The range was then divided into four intervals. Expert B provided an assessment of ignition probability at the endpoints of each interval. Once he had selected a best-estimate ignition probability for each selected concentration (based on his judgment), a beta distribution was selected which approximately represented his judgment as to the uncertainty in that assessment. The

appropriate beta distribution was selected from a book of beta distribution plots. The results are provided below in Table B-1. Beta distributions were specified by two parameters, the mode (interpreted to correspond with Expert B's best guess at the ignition probability), and a spread factor of (n) which corresponds with either the parameter P or the parameter Q (depending on the value of the mode) in the standard formulation of the beta distribution. The distributions in Table B-1 are shown graphically in Figures B-1 through B-4.

Table B-1
Distributions

Hydrogen Concentration (mole fraction)	Median	Mode	Spread Factor (n)
≤ 4%	0.0	0.0	n/a
8%	0.07	0.04	20
12%	0.11	0.08	20
16%	0.16	0.14	10
≥ 20%	0.27	0.20	5

Expert B indicated that the ignition probability for hydrogen concentrations within an interval could be obtained by linear interpolation of the values at the endpoints.

Sources of Uncertainty

The principal source of uncertainty was identified by Expert B as being that there were no clearly identified ignition sources.

Part 2

Description of the Expert B's Rationale/Methodology

Expert B based his assessment on an assumed likelihood for hot gas from the drywell to enter the containment at vessel breach. He believed that the level in the suppression pool would be severely depressed before vessel breach. Rapid hydrogen flow into the containment before vessel breach was cited as the primary cause for the overflow of suppression pool water onto the drywell floor.

Given the very short distance between the level of the suppression pool and the top row of vents, Expert B felt that it is not unlikely that hot gas could flow from the drywell into the wetwell without equilibrating

Figure B-1. Frequency of Ignition; 8% Mole Fraction Hydrogen--Low Steam.

Figure B-2. Frequency of Ignition; 12% Mole Fraction Hydrogen--Low Steam.

Figure 8-3. Frequency of Ignition; 16% Mole Fraction Hydrogen--Low Steam.

Figure 8-4. Frequency of Ignition; 20% Mole Fraction Hydrogen--Low Steam.

with the pool water. He felt that it is unlikely that hot debris could pass into the wetwell, but the hot gas might be sufficient for an ignition. Any high pressure melt ejection is directed at the weir wall, and steam, exiting the vessel, is heated by the debris in the vicinity of the top of the weir well. It is noteworthy that the average drywell temperature is on the order of 1000 to 1300 K for a 50% debris ejection case as seen in Figure 20 of the Murata Report presented in NUREG/CR-4551, Vol. 2, Part 5. Thus the local temperature could be much higher. These temperatures are sufficient to result in ignition, but because some cooling by the pool would occur, ignition is less than certain.

As for Part 1 of this issue, ignition probability increases with increasing hydrogen concentration. Uncertainty in the ignition probability also increases with increasing hydrogen concentration. Because the ignition source is identifiable for the situation considered here, Expert B expressed that his uncertainty about a given best-estimate value for ignition probability was slightly lower than in Part 1.

Results of Expert B's Elicitation

Expert B judged that ignition from hot gas being ejected into the drywell was three times more likely than ignition due to random sources before vessel breach.

The same procedure for this assessment was used as that in Part 1. Table B-2 shows the beta distributions that were selected. These are shown graphically in Figures B-5 through B-8.

Table B-2
Selected Beta Distributions

Hydrogen Concentration (mole fraction)	Median	Mode	Spread Factor (n)
≤ 4%	0.0	0.0	n/a
8%	0.15	0.12	15
12%	0.28	0.25	10
16%	0.5	0.5	10
≥ 20%	0.58	0.6	5

Again, Expert B indicated that the ignition probability for hydrogen concentrations within an interval could be obtained by linear interpolation of the values at the endpoints.

Sources of Uncertainty

As for the situation before vessel breach, uncertainty stems from whether or not an ignition source is present. Gas blown from the drywell may not be hot enough to cause ignition.

Figure B-5. Frequency of Ignition at Vessel Breach 8% Mole Fraction Hydrogen.

Figure B-6. Frequency of Ignition at Vessel Breach 12% Mole Fraction Hydrogen.

Figure B-7. Frequency of Ignition at Vessel Breach 16% Mole Fraction Hydrogen.

Figure B-8. Frequency of Ignition at Vessel Breach 16% Mole Fraction Hydrogen.

Part 3

Description of Expert B's Rationale/Methodology

Static Pressure Load

Expert B based his assessment on the AICC pressure resulting from combustion of a given molar concentration of hydrogen. This maximum pressure was modified based on the Expert's judgment about the likely completeness of the burn.

Detonation was assessed to be impossible below a hydrogen mole fraction of 16%. Detonation probabilities and loads were assessed separately (see below).

The adiabatic pressure rise was assessed for two different levels of in-vessel zirconium reaction: 10 and 50%. These levels were converted to an equivalent global hydrogen concentration in the containment. The AICC pressure was then determined based on these concentrations. These results are shown in Table B-3.

Table B-3
Results for Adiabatic Burn Pressure

In-Vessel Zirconium Reaction	Adiabatic Burn Pressure			Maximum Pressure (bar)
	Hydrogen (MF)	Steam (MF)	Air (MF)	
10%	0.079	0.26	0.66	5
50%	0.29	0.19	0.52	12.5

The Expert based his assessment of burn completeness on: (a) research results that compare peak pressures obtained during combustion experiments at various burn facilities with the corresponding AICC pressures; (b) discussions with other panel members; and (c) his knowledge of hydrogen phenomena. Again, a beta distribution was chosen to reflect Expert B's judgment about the uncertainty in burn completeness. The completeness of burn was thought to increase with increasing hydrogen concentration. Expert B again selected a beta distribution to reflect his judgment about the uncertainty in burn completeness. The completeness of combustion was thought to increase with increasing hydrogen concentration. In general, Expert B's uncertainty in the completeness of the burn was independent of the hydrogen concentration. He thought that reverse vent-clearing, allowing gas flow from the containment to the drywell would have a negligible impact on peak pressure because the time for flow to occur was long relative to the time required for combustion.

Expert B believed that Cases 1 and 2 for this part of the issue would behave identically. Sprays are initiated too late in Case 2 to impact the peak pressure attained. He found that Case 3 would be different in that more steam would be present in the containment when ignition

occurred. Expert B stated that burn completeness would be unaffected (within the bounds of his uncertainty) by the sprays. Thus, for Case 3, the pressure attained would be reduced because the burn was slower, but the burn completeness remains the same as for the low-steam Cases 1 and 2 for a given hydrogen concentration.

Detonation Load

Expert B based his assessment of dynamic loads largely on the work presented by Expert A. Following that expert, he stated that a detonation would produce a load that was independent of the hydrogen concentration at which ignition occurred. He felt that there was little uncertainty in the load induced.

However, the probability of a detonation occurring was seen to be strongly dependent on the presence of a minimum hydrogen concentration (16% MF). He stated that with 20% steam present the detonation cell width is only 100 mm, and with the containment volume being large and relatively open, a detonation was very unlikely.

Results of Expert B's Elicitation

As for ignition probability, the range of possible hydrogen concentrations was divided into intervals. No assessment was made for greater than 16% hydrogen mole fraction. Expert B felt that at 20% hydrogen mole fraction the burn completeness would be at least 90% with little uncertainty. This results in a peak static pressure of at least 8 bar (116 psia) which is so much greater than the assessed containment failure pressure (71 psia) that elicitation of static pressure in this range would not benefit the analysis (i.e., containment failure could be assumed certain). A beta distribution on burn completeness was selected, based on the Expert's judgment, for each hydrogen concentration selected to discretize the range. These distributions are characterized in Table B-4. The distributions in Table B-4 are shown graphically in Figures B-9 through B-11.

Table B-4
Distribution of Burn Completeness

Hydrogen Concentration (mole fraction)	Median	Mode	Spread Factor (n)
≤ 4%	0.0	0.0	n/a
8%	0.50	0.50	50
12%	0.70	0.70	50
16%	0.84	0.85	50
≥ 20%	0.90	0.90	n/a

Completeness for hydrogen concentration within an interval is estimated based on linear interpolation for values at the endpoints.

Figure B-9. Completeness of Hydrogen Burn; 8% Mole Fraction Hydrogen.

Figure B-10. Completeness of Hydrogen Burn; 12% Mole Fraction Hydrogen.

Figure B-11. Completeness of Hydrogen Burn; 16% Mole Fraction Hydrogen.

Once the burn completeness is obtained, the static pressurization of the containment is calculated by multiplying the adiabatic burn pressure ratio by the burn completeness. For Case 3 of this part of the issue, where the steam concentration is high (i.e., near the limit for inerting) and sprays operate, Expert B reduced the burn pressure ratio an additional 25%. No reduction in uncertainty relative to completeness was added to account for enhanced mixing by the sprays.

Detonation Load

Expert B provided a probability for detonation, given that ignition occurs, as a beta distribution applicable for hydrogen concentrations greater than 20% mole fraction. The beta distribution, shown in Figure B-12, is characterized by a mode of 0.10 with a spread characterized by $n = 10$. The mean of this distribution is 0.15. For hydrogen concentrations between 16 and 20%, the probability obtained from this distribution would be reduced linearly (to 0 at 16% MF). Expert B believed that there was little uncertainty associated with the dynamic load on the drywell wall. A mean value of 12 kPa-s was believed to be appropriate based on presentations by Expert A. The upper and lower bounds (which should be interpreted as 5th and 95th percentile values) were taken as 18 kPa-s and 6 kPa-s, respectively. A maximum entropy distribution is assumed as shown in Figure B-13.

Figure B-12. Frequency of Detonation; At Least 20% Mole Fraction Hydrogen.

Figure B-13. Grand Gulf Detonation Loads.

Sources of Uncertainty

Static Pressure Load

Provided ignition occurs, burn completeness is believed to be the greatest uncertainty. Generally, the uncertainty in the loads produced is small relative to the ignition probability.

Dynamic Load

Expert B believed that detonation loads are relatively well understood and have little associated uncertainty. Again, the probability of a detonation occurring governs this uncertainty.

Expert C's Elicitation

Issue 1. Hydrogen Phenomenon at Grand Gulf

Description of Expert C's Rationale/Methodology

Expert C analyzed the problem using the following procedure:

1. For Step 1, the three initial cases were subdivided into three subcases each on the basis of 10, 30 and 50% of cladding and 5, 15, and 25% of channel boxes reacting.
2. For Step 2, release before vessel failure, the Expert constructed a CDF for average concentration based on the results of computer code runs for each of the cases in Step 1.
3. For Step 3, the Expert constructed a CDF for peak concentration taking into account his judgment about the effects of nodalization and mixing on the realistic peak concentrations expected.
4. For Step 4, the Expert assessed the probability of ignition vs. peak concentration with uncertainty bounds.
5. For Step 5, the Expert assessed the split fraction for the resulting combustion being a diffusion flame, a deflagration, or a detonation vs. peak concentration level.
6. For Step 6, the Expert assessed the peak pressure or impulse vs. peak concentration.

The Expert used the following cases:

1. H₂ ignition before vessel breach (1a--vessel at high pressure; 2a--vessel at low pressure);
2. H₂ ignition at vessel breach (3a);
3. Containment loads (1b--low steam, no sprays; 2b--low steam, sprays).
4. Containment loads (3b--high steam, sprays).

Results of Expert C's Elicitation

Results of the Expert's analysis for each of the cases are given below:

Step 2, Average concentration for all cases (1a/2a/3a).

	<u>Quartile</u>				
	.0	.25	.5	.75	1.0
10%	.03	.04	.045	.048	.05
30%	.08	.095	.11	.12	.13
50%	.13	.15	.17	.185	.20

Steps 3 and 3', Peak concentration (1a/2a, 3a).

To go from average to peak concentration, sample the average concentration curve; then pick the same quartile for the peak concentration.

Case 1a/2a (Step 3):

	<u>Quartile</u>				
	.0	.25	.5	.75	1.0
10%	.03	.04	.05	.06	.08
30%	.08	.10	.115	.13	.16
50%	.13	.15	.175	.2	.23

Case 3a (Step 3'):

	<u>Quartile</u>				
	0	.25	.5	.75	1.0
10%	.05	.052	.055	.065	.08
30%	.15	.152	.155	.165	.18
50%	.23	.233	.24	.25	.26

For this analysis, the concentration will be determined by other experts. Therefore, we convert the peak concentration to average concentration for the various subcases, which differentiate between the extent of the zirconium reaction. From the in-vessel group, we obtained the probability of the in-vessel melt progression reacting $x\%$ of the total zirconium. This Expert's value of $x\%$ zirconium in cladding and $x/2\%$ of the rest converts to (1) $50 + 25\% = 40\%$, (2) $30 + 15\% = 24\%$, and (3) $10 + 5\% = 8\%$ total zirconium reacted. By grouping the in-vessel experts' results, we can weight the medium and high zirconium cases in order to average over them at points where the cases overlap. For the two in-vessel cases: (1) 0 to 16%

zirconium was .2 and .17, (2) 16 to 32% zirconium was .48 and .47, (3) 32% to 56 or 64 % zirconium was .32 and .36. Averaging low = .185, medium = .475, high = .34 and the weights are .583 for medium and .417 for high.

<u>Average Concentration</u>	<u>Peak Concentration</u>					
	<u>1a/2a</u>			<u>3a</u>		
	<u>10%</u>	<u>30%</u>	<u>50%</u>	<u>10%</u>	<u>30%</u>	<u>50%</u>
.03	.03	-	-	.05	-	-
.4	.04	-	-	.052	-	-
.045	.05	-	-	.055	-	-
.048	.06	-	-	.065	-	-
.05	.08	-	-	.08	-	-
.08	-	.08	-	-	.15	-
.095	-	.10	-	-	.152	-
.11	-	.115	-	-	.155	-
.12	-	.13	-	-	.165	-
.13	-	.16	.13	-	.18	.23
.15	-	-	.15	-	-	.233
.17	-	-	.175	-	-	.24
.185	-	-	.2	-	-	.25
.2	-	-	.23	-	-	.26

By averaging, the three scenarios can be combined as follows:

<u>Average Concentration</u>	<u>Peak Concentration</u>	
	<u>1a/2a</u>	<u>3a</u>
.03	.03	.05
.04	.04	.052
.045	.05	.055
.048	.06	.065
.05	.08	.08
.08	.08	.15
.095	.10	.152
.11	.115	.155
.12	.13	.165
.13	.143	.20
.15	.15	.233
.17	.175	.24
.185	.20	.25
.2	.23	.26

Steps 4 and 5, ignition probability and split fraction.

Case 1a/2a: Ignition Probability

	<u>Peak Concentration</u>						
	.02	.04	.08	.12	.16	.20	.24
.95 fractile	0	0	.125	.3	.55	.7	.75
.50 fractile	0	0	.05	.15	.4	.55	.60
.05 fractile	0	0	.025	.1	.35	.475	.50

	<u>Average Concentration 10%</u>				
	.03	.04	.045	.048	.05
.95 fractile	0	0	.042	.083	.125
.50 fractile	0	0	.017	.033	.05
.05 fractile	0	0	.008	.017	.025

	<u>Average Concentration 30%</u>				
	.08	.095	.11	.12	.13
.95 fractile	.125	.213	.278	.363	.55
.50 fractile	.05	.10	.138	.213	.40
.05 fractile	.025	.063	.091	.163	.35

	<u>Average Concentration 50%</u>				
	.13	.15	.17	.185	.20
.95 fractile	.363	.488	.606	.725	.75
.50 fractile	.213	.338	.456	.575	.60
.05 fractile	.163	.288	.397	.488	.50

Case 3a: Multiplier of Case 1a/2a

	<u>Peak Concentration</u>					
	.04	.08	.12	.16	.20	.24
Blowdown	1.1	1.1	1.1	1.1	1.05	1.05
Blowdown + HPME	1.5	1.5	1.5	1.4	1.3	1.3
Blowdown + Expl.	1.2	1.2	1.2	1.2	1.2	1.2
DW hydrogen burn	1.5	1.4	1.3	1.2	1.2	1.05
Average	1.3	1.3	1.3	1.2	1.2	1.2

To get the probability of ignition at vessel breach, multiply the ignition probability for the case before vessel breach by the appropriate case. However, the in-vessel panel for boiling water reactor (BWR) bottom head failure did not give enough information to separate the various cases. We will therefore average over the cases.

	<u>Peak Concentration</u>						
	.02	.04	.08	.12	.16	.20	.24
.95 fractile	0	0	.163	.39	.66	.84	.90
.50 fractile	0	0	.065	.195	.48	.66	.72
.05 fractile	0	0	.033	.13	.42	.57	.60

	<u>Average Concentration 10%</u>				
	.03	.04	.045	.048	.05
.95 fractile	.041	.049	.061	.083	.163
.50 fractile	.016	.020	.024	.033	.065
.05 fractile	.008	.010	.012	.017	.033

	<u>Average Concentration 30%</u>				
	.08	.095	.11	.12	.13
.95 fractile	.593	.606	.626	.683	.75
.50 fractile	.409	.423	.444	.503	.57
.05 fractile	.348	.362	.384	.439	.495

	<u>Average Concentration 50%</u>				
	.13	.15	.17	.185	.20
.95 fractile	.885	.890	.90	.90	.90
.50 fractile	.705	.710	.72	.72	.72
.05 fractile	.593	.595	.60	.60	.60

<u>Average Concentration</u>	<u>Ignition Probability</u>					
	<u>1a/2a</u>			<u>3a</u>		
	<u>.95</u>	<u>.50</u>	<u>.05</u>	<u>.95</u>	<u>.50</u>	<u>.05</u>
.03	.0	.0	.0	.041	.016	.008
.04	.0	.0	.0	.049	.02	.01
.045	.042	.017	.008	.061	.024	.012
.048	.083	.033	.017	.083	.033	.017
.05	.125	.05	.025	.163	.065	.033
.08	.125	.05	.025	.593	.409	.348
.095	.213	.10	.063	.606	.423	.362
.11	.278	.138	.091	.626	.444	.384
.12	.363	.213	.163	.683	.503	.439
.13	.472	.322	.272	.806	.626	.536
.15	.488	.338	.288	.890	.710	.595
.17	.606	.456	.397	.90	.72	.60
.185	.725	.575	.488	.90	.72	.60
.2	.75	.60	.50	.90	.72	.60

Case 1a/2a/3a: Split fraction

	<u>Peak Concentration</u>						
	<u>.02</u>	<u>.04</u>	<u>.08</u>	<u>.12</u>	<u>.16</u>	<u>.20</u>	<u>.24</u>
Diffusion Flame	0	.5	.5	0	0	0	0
Deflagration	0	.5	.5	1	.65	.45	.25
Detonation	0	0	0	0	.35	.55	.75

For Case 1a/2a

	<u>Average Concentration 10%</u>				
	<u>.03</u>	<u>.04</u>	<u>.045</u>	<u>.048</u>	<u>.05</u>
Diffusion	0	.5	.5	.5	.5
Deflagration	0	.5	.5	.5	.5
Detonation	0	0	0	0	0

	<u>Average Concentration 30%</u>				
	<u>.08</u>	<u>.095</u>	<u>.11</u>	<u>.12</u>	<u>.13</u>
Diffusion	.5	.25	.062	0	0
Deflagration	.5	.75	.938	.912	.65
Detonation	0	0	0	.088	.35

	<u>Average Concentration 50%</u>				
	.13	.15	.17	.185	.20
Diffusion	0	0	0	0	0
Deflagration	.912	.738	.575	.45	.3
Detonation	.088	.262	.425	.55	.7

For Case 3a

	<u>Average Concentration 10%</u>				
	.03	.04	.045	.048	.05
Diffusion	.5	.5	.5	.5	.5
Deflagration	.5	.5	.5	.5	.5
Detonation	0	0	0	0	0

	<u>Average Concentration 30%</u>				
	.08	.095	.11	.12	.13
Diffusion	0	0	0	0	0
Deflagration	.738	.72	.694	.55	.45
Detonation	.262	.28	.306	.45	.55

	<u>Average Concentration 50%</u>				
	.13	.15	.17	.185	.20
Diffusion	0	0	0	0	0
Deflagration	.3	.285	.25	.25	.25
Detonation	.7	.715	.75	.75	.75

	<u>Mode of Combustion</u>					
	<u>1a/2a</u>			<u>3a</u>		
<u>Average Concentration</u>	<u>DF</u>	<u>DEF</u>	<u>DET</u>	<u>DF</u>	<u>DEF</u>	<u>DET</u>
.03	.0	.0	.0	.5	.5	.0
.04	.5	.5	.0	.5	.5	.0
.045	.5	.5	.0	.5	.5	.0
.048	.5	.5	.0	.5	.5	.0
.05	.5	.5	.0	.5	.5	.0
.08	.5	.5	.0	.0	.738	.262
.095	.25	.75	.0	.0	.72	.28
.11	.062	.938	.0	.0	.694	.306

<u>Mode of Combustion (continued)</u>						
<u>Average Concentration</u>	<u>1a/2a</u>			<u>3a</u>		
	<u>DF</u>	<u>DEF</u>	<u>DET</u>	<u>DF</u>	<u>DEF</u>	<u>DET</u>
.12	.0	.912	.088	.0	.55	.45
.13	.0	.759	.241	.0	.388	.613
.15	.0	.738	.262	.0	.285	.715
.17	.0	.575	.425	.0	.25	.75
.185	.0	.45	.55	.0	.25	.75
.2	.0	.30	.70	.0	.25	.75

Step 6, Peak pressure, all cases (1a/2a/3a).

Peak pressure (bars) diffusion flames

<u>Peak Concentration</u>	<u>Case 1b/2b</u>	<u>Case 3b</u>
.04	1.25	1.25
.08	1.75	2.25
.12	2.25	3.00

Case 1b/2b

<u>Average Concentration 10%</u>					
	.03	.04	.045	.048	.05
Peak Pressure	0	1.25	1.38	1.50	1.75

<u>Average Concentration 30%</u>					
	.08	.095	.11	.12	.13
Peak Pressure	1.75	2.00	2.19	2.25	-

<u>Average Concentration 50%</u>					
	.13	.15	.17	.185	.20
Peak Pressure	-	-	-	-	-

Case 3b

	<u>Average Concentration 10%</u>				
Peak Pressure	.03 1.38	.04 1.40	.045 1.44	.048 1.56	.05 1.75

	<u>Average Concentration 30%</u>				
Peak Pressure	.08 -	.095 -	.11 -	.12 -	.13 -

	<u>Average Concentration 50%</u>				
Peak Pressure	.13 -	.15 -	.17 -	.185 -	.20 -

Peak Pressure (bars) deflagrations or post-impulse detonations

<u>Peak Concentration</u>	<u>Case 1b/2b</u>	<u>Case 3b</u>
.04	1.25	1.75
.08	3.00	4.25
.12	4.50	6.25
.16	5.50	7.75
.22	6.00	9.00
.26	6.50	10.00

Case 1b/2b

	<u>Average Concentration 10%</u>				
Peak Pressure	.03 -	.04 1.25	.045 1.69	.048 2.12	.05 3.00

	<u>Average Concentration 30%</u>				
Peak Pressure	.08 3.00	.095 3.75	.11 4.31	.12 4.75	.13 5.50

	<u>Average Concentration 50%</u>				
Peak Pressure	.13 4.75	.15 5.25	.17 5.62	.185 5.83	.20 6.12

Case 3b

<u>Average Concentration 10%</u>					
	.03	.04	.045	.048	.05
Peak Pressure	2.38	2.50	2.69	3.31	4.25

<u>Average Concentration 30%</u>					
	.08	.095	.11	.12	.13
Peak Pressure	7.38	7.45	7.56	7.85	8.17

<u>Average Concentration 50%</u>					
	.13	.15	.17	.185	.20
Peak Pressure	9.25	9.32	9.50	9.75	10.00

The initial pressure given by the Expert is not what we calculate, so we will adjust by subtracting 1.25 and 1.75 for 1b/2b and 3b diffusion flame and add back 1.65 for 1b/2b and 2.55 for 3b.

<u>Peak Pressure</u>				
<u>1a/2a</u>			<u>3a</u>	
<u>Average Concentration</u>	<u>DF</u>	<u>DEF/DET</u>	<u>DF</u>	<u>DEF/DET</u>
.03	-	-	1.38	2.38
.04	1.25	1.25	1.40	2.50
.045	1.38	1.69	1.44	2.69
.048	1.50	2.12	1.56	3.31
.05	1.75	3.00	1.75	4.25
.08	1.75	3.00	-	7.38
.095	2.00	3.75	-	7.45
.11	2.19	4.31	-	7.56
.12	2.25	4.75	-	7.85
.13	-	5.19	-	8.62
.15	-	5.25	-	9.32
.17	-	5.62	-	9.50
.185	-	5.83	-	9.75
.2	-	6.12	-	10.0

<u>Average Concentration</u>	<u>Peak Pressure (adjusted)</u>			
	<u>1a/2a</u>		<u>3a</u>	
	<u>DF</u>	<u>DEF/DET</u>	<u>DF</u>	<u>DEF/DET</u>
.03	-	-	2.68	3.18
.04	1.65	1.65	2.70	3.30
.045	1.78	2.09	2.74	3.49
.048	1.90	2.52	2.86	4.11
.05	2.15	3.40	3.05	5.05
.08	2.15	3.40	-	8.18
.095	2.40	4.15	-	8.25
.11	2.59	4.71	-	8.36
.12	2.65	5.15	-	8.65
.13	-	5.59	-	9.42
.15	-	5.65	-	10.12
.17	-	6.02	-	10.3
.185	-	6.23	-	10.55
.2	-	6.52	-	10.8

Peak Impulse (kPa-s)

<u>Peak Concentration</u>	<u>Fractiles</u>		
	.05	.50	.95
.12	0	0	0 (our extrapolation)
.16	1.00	1.00	1.00
.20	1.50	2.00	4.50
.24	4.00	5.00	10.00
.26	6.50	8.00	15.00

Case 1b/2b

	<u>Average Concentration 10%</u>				
	0.03	0.04	0.045	0.048	0.05
.95 Impulse	0	0	0	0	0
.50 Impulse	0	0	0	0	0
.05 Impulse	0	0	0	0	0

	<u>Average Concentration 30%</u>				
	0.08	0.095	0.11	0.12	0.13
.95 Impulse	0	0	0	0.25	1
.50 Impulse	0	0	0	0.25	1
.05 Impulse	0	0	0	0.25	1

		<u>Average Concentration 50%</u>				
		0.13	0.15	0.17	0.185	0.20
.95	Impulse	1	1	2.31	4.5	7.25
.50	Impulse	1	1	1.38	2	3.50
.05	Impulse	1	1	1.19	1.5	2.75

Case 3b

		<u>Average Concentration 10%</u>				
		.03	.04	.045	.048	.05
.95	Impulse	-	-	-	-	-
.50	Impulse	-	-	-	-	-
.05	Impulse	-	-	-	-	-

		<u>Average Concentration 30%</u>				
		.08	.095	.11	0.12	0.13
.95	Impulse	.875	.9	.94	1.44	2.75
.50	Impulse	.875	.9	.94	1.12	1.50
.05	Impulse	.875	.9	.94	1.06	1.25

		<u>Average Concentration 50%</u>				
		0.13	0.15	0.17	0.185	0.20
.95	Impulse	8.62	9.04	10.0	12.5	15.0
.50	Impulse	4.25	4.48	5.00	6.50	8.00
.05	Impulse	3.38	3.56	4.00	5.25	6.50

		<u>Peak Impulse</u>					
<u>Average Concentration</u>		<u>1b/2b</u>			<u>3b</u>		
		.95	.50	.05	.95	.50	.05
	.03	-	-	-	-	-	-
	.04	-	-	-	-	-	-
	.045	-	-	-	-	-	-
	.048	-	-	-	-	-	-
	.05	-	-	-	0	0	0
	.08	-	-	-	.75	.75	.75
	.095	-	-	-	.8	.8	.8
	.11	0	0	0	.875	.875	.875
	.12	.25	.25	.25	1.44	1.12	1.06
	.13	.583	.583	.583	5.20	2.65	2.14
	.15	1.00	1.00	1.00	9.04	4.48	3.56

<u>Average Concentration</u>	<u>Peak Impulse (continued)</u>					
	<u>1b/2b</u>			<u>3b</u>		
	.95	.50	.05	.95	.50	.05
.17	2.31	1.38	1.19	10.0	5.00	4.00
.185	4.50	2.00	1.50	12.5	6.50	5.25
.2	7.25	3.50	2.75	15.0	8.00	6.50

Sources of Uncertainty

The Expert in his assessment of quartiles for the concentration level for each case's three scenarios accounts for the uncertainty due to the amount of hydrogen produced. Uncertainty in the efficiency of mixing is accounted for by a factor used to modify the average concentration curves to get peak concentration curves for the various cases; quartiles were assessed. Uncertainty in the probability of combustion was represented in .05, .50, and .95 confidence curves for the probability of ignition vs. concentration level. Uncertainty in the mode of combustion was accounted for by a split fraction over the various modes vs. concentration level. Uncertainties in the detonation impulse was assessed vs. initial peak concentration level by .05, .50, and .95 bounds. Uncertainty bounds were not assessed for the peak pressures.

Correlations with Other Variables

The external variables of hydrogen and steam concentration were used as input variables; these need to be related to the in-vessel melt and bottom head failure scenarios in order to correlate with hydrogen production variables. The amount burned needs to be subtracted from any subsequent production.

Suggested Methods for Reducing Uncertainty

No explicit recommendations were made for reducing uncertainty.

5.2 Containment Loads Issue 2. Hydrogen Burn Before Vessel Breach at Sequoyah

Summary of Expert Panel's Assessment of Issue 2:
Hydrogen Burn Before Vessel breach at Sequoyah

Experts consulted: James Metcalf, Stone & Webster; Martin Sherman, Sandia National Laboratories; Pat Worthington, Nuclear Regulatory Commission.

Issue Description

What distributions characterize the loads to containment due to hydrogen combustion prior to vessel breach at Sequoyah? What distributions characterize the loads in the ice condenser due to detonations in the ice condenser prior to vessel breach at Sequoyah?

Case Structure

All the cases are for the condition of neither igniters nor air return fans operating. The principal sequence is station blackout with failure of auxiliary feedwater.

Case 1. The reactor coolant system (RCS) is at the system setpoint pressure of 17.2 MPa (2500 psia). The only release from the RCS is via a periodically cycling power-operated relief valve (PORV).

Case 2. The RCS was initially at high pressure, but a leak has developed in the reactor coolant pump (RCP) seals, equivalent to an S3 cold leg loss-of-coolant accident (LOCA).

Case 3. The RCS was initially at high pressure, but a LOCA of intermediate size has developed in the hot leg, equivalent to a stuck open PORV.

Case 4. The RCS was initially at high pressure, but a large LOCA has developed in the hot legs, equivalent to a temperature-induced hot leg or pressurizer surge line failure.

Summary of Experts' Rationale

Expert A reviewed relevant sequence calculations from NUREG/CR-3912,^{A-1} Haskin et al.,^{A-2} BMI-2104,^{A-3} IDCOR Task 23.1,^{A-4} IDCOR Task 85.5A,^{A-5} and BMI-2139.^{A-6} A crucial point in this Expert's decomposition was whether or not the upper plenum and the dome were well mixed. If several of the upper deck doors were to remain closed, failure to mix could occur. However, it was considered probable that the upper deck doors would be open and that the probability of upper plenum mixing could not be lower than 0.5. If the upper plenum and dome were not mixed, the hydrogen concentrations in the upper plenum and the ice condenser were expected to be approximately the same.

Separate distributions for the frequency of ignition were given for three ranges of hydrogen mole fractions. These ranges were: 0.06 to 0.10, 0.10 to 0.14, and > 0.14 . The ignition energy should be delivered in a very short time, with very high spatial density, even though the total energy requirements were quite low. The Expert therefore selected relatively low values for frequency of ignition; the maximum frequency cited was estimated to be 0.5. As leaner mixtures require more energy for detonation, the frequency of detonation was reduced for lower mole fractions.

This Expert considered that if ignition sources were present at all, they were more likely to be in the upper plenum than in the ice condenser. The reduced probability of ignition in the ice condenser was handled by multiplying the distributions for frequency of ignition in the upper plenum by a distribution which is always less than 0.5. If ignition occurs, detonation is only possible if the hydrogen mole fraction exceeds 0.14. For mole fractions less than this, every combustion event is a deflagration.

If combustion is a deflagration, the peak pressures are functions of mole fraction of hydrogen. Since detonation can only occur for mole fractions exceeding 0.14, impulses are not functions of concentration. Expert A considered that burning, if it occurred, would be complete, or nearly so.

Expert A assigned the greatest uncertainty to the mixing of the upper plenum and dome, although considerable uncertainty was also assigned to the probability of ignition.

Expert B reviewed calculations from NUREG/CR-3912,^{B-1} SAND85-1824C,^{B-2} Haskin et al.,^{B-3} and IDCOR Task 23.1.^{B-4} He placed the greatest reliance on References B-1 and B-2. The Expert provided a decomposition tree which was evaluated and solved by a Monte Carlo method. The simplified logic of the tree is that the necessary conditions for combustion would be that an ignition source must be available; that it must be in the ice condenser, upper plenum, or dome; and that the gas mix in the compartment where the ignition source occurs must be flammable or detonable. The cases were not distinguished; however, the decomposition is somewhat different for low and high zirconium oxidation levels.

The Expert assessed flammability by observing the calculated gas composition over a 1000-s time period. The probability that the mixture was flammable at any time was taken to be the fraction of time that the mixture was in the flammable regime. Detonability was considered possible only in the ice condenser and was addressed in the same manner as flammability.

Expert B decided to use the model for pressure rise due to a deflagration in the dome provided by Expert C. The model uses the AICC pressure ratio, with corrections made for burn completeness, heat transfer to solid surfaces, and adiabatic expansion into nonparticipating volumes. Pressures in the ice condenser and upper plenum lie considerably below the distributions taken from the Structural Response Expert Panel for containment

failure. The Expert indicated that burn completion was to be estimated using the model of Wong.^{B-5}

Distributions for the masses of hydrogen in each compartment were not given. The method described in the method of aggregation section for estimating mole fractions in each compartment was used.

Expert C's rationale for the quantification of this issue is presented in two papers that appear as Attachments A and B at the end of Expert C's detailed elicitation.

Expert C considered the presence of an ignition source to be the essential uncertainty for this issue, because code calculations predict detonable mixtures within the ice condenser for appreciable periods during this sequence. If igniters and fans are operating, hydrogen is never a problem. The most likely ignition source was evaluated to be the contact between the metal intermediate deck doors.

Combustion was considered in the ice condenser, the upper plenum, and the dome; the concentration in the dome was only flammable for the highest level of in-vessel hydrogen production and only towards the end of the accident. Expert C gave a rather low likelihood for combustion in the dome. The ice condenser would have been detonable for long periods of time before the dome is flammable and would have much more chance of a damaging combustion, involving acceleration to detonation.

Deflagrations would be of importance only if they occurred in the dome. The amount of hydrogen in the ice condenser or upper plenum is too small to be of any consequence for deflagration. Expert C, therefore, restricted the focus to events which would lead to detonation in the ice condenser or deflagration in the dome.

Method of Aggregation

Relationship to Accident Progression Event Tree

The following questions in the accident progression event tree (APET) are evaluated using the data elicited in this issue:

1. What fraction of the hydrogen produced in the vessel is released to containment before vessel breach?
2. What fraction of the hydrogen is transmitted to the ice condenser, upper plenum of the ice condenser, and upper compartment (dome)?
3. Does ignition occur in the ice condenser?
4. Does ignition occur in the upper plenum?
5. Does ignition occur in the dome?
6. Does combustion propagate to the dome from other compartments?

7. Does deflagration-to-detonation transition (DDT) occur in the ice condenser?
8. Does DDT occur in the upper plenum?
9. What is the impulse in the ice condenser or upper plenum?
10. What is the pressure in containment?

The fraction of hydrogen released from the RCS before vessel breach was assessed using Expert A's distribution [1], from Table A-8. (Distributions are indicated by bracketed symbols, e.g., [A].) The other experts did not provide data for this question, but agreed to use Expert A's data.

Experts A and C provided data on mixing of hydrogen into the dome. Expert A's distribution [B] gives the probability that the upper plenum and dome will be well-mixed. Good mixing occurs between the upper plenum and dome when several upper deck doors (essentially made of blanket insulation) are thrown open. The amount of hydrogen in the dome in the well-mixed case was assumed to be 100% of the amount predicted by HECTR calculations,^{A-1} reported in Table 2-1 below. The amount in the unmixed case was estimated to be 10% of the amount predicted by HECTR. Expert C estimated probability of a clear path to be 0.1. A clear path occurs when several intermediate deck doors are open. When a clear path was available, 100% of the hydrogen predicted by HECTR was used. In the absence of a clear path, 50% of the amount predicted by HECTR was assumed to be in the dome. Table 2-2 below shows the fraction F_{UC} , which is to be applied to the HECTR predicted fraction from Table 2-1. The fraction which is not admitted to the dome, $1-F_{UC}$, is distributed through the remaining compartments in the same ratios as were predicted by HECTR.

Table 2-1
Distribution of Hydrogen in Containment;
Compartmental Fraction of Total
Hydrogen Released from the RCS

<u>Compartment</u>	<u>HECTR Prediction (Cases 1, 2, 3, and 4)</u>	<u>CONTAIN Prediction (Alternate Case 2)</u>
Lower Compartment	0.35	0.44
Ice Condenser	0.36	0.13
Upper Plenum of Ice Condenser	0.03	0.01
Upper Compartment	0.26	0.42

For Case 2, Expert C cited a CONTAIN calculation that indicated that the majority of the steam and hydrogen would flow through an open drain line, effectively bypassing the ice condenser. The concentration of hydrogen in containment for the bypass condition is provided in Table 2-1. Expert C estimated a 50% probability that the CONTAIN calculation was realistic.

Table 2-2
Mixing of Hydrogen Into the Dome

<u>F_{HC} Percent</u>	<u>Probability</u>	<u>Cumulative Probability</u>
10	0.1042	0.1042
50	0.4500	0.5542
100	0.5542	1.0000

Because the results of Experts A and C are being averaged to assess hydrogen distribution, 25% was taken to be the aggregated probability of the bypass condition that is indicated by the CONTAIN calculation.

Frequency of ignition in the ice condenser and upper plenum was assessed by all three experts. Experts A and C used slightly different ranges of hydrogen concentration for assessing the effect of concentration. For the purposes of aggregation, the mole fraction boundaries have been averaged for the two experts. Expert B, on the other hand, gave the same distribution for any mole fraction. Ignition will not be allowed in any case if the hydrogen mole fraction is below 5.5%. Only Experts B and C provided distributions for frequency of ignition in the dome. A distribution was not provided by Expert A due to the assumption that the concentration of hydrogen in the dome would never attain the flammable limit.

Aggregated Results

Tables 2-3 through 2-5 show frequencies of ignition for the ice condenser, upper plenum, and dome, for the three ranges of mole fractions.

Table 2-3
Distribution For Ignition Frequency in the Ice Condenser

<u>Cumulative Probability</u>	<u>Ignition Frequency in Ice Condenser For Hydrogen Mole Fraction Ranges</u>		
	<u>H₂ mf 5.5-11%</u>	<u>H₂ mf 11-16%</u>	<u>H₂ mf >16%</u>
0.01	0.000	0.010	0.009
0.05	0.002	0.024	0.067
0.25	0.014	0.065	0.134
0.50	0.127	0.144	0.169
0.75	0.189	0.215	0.252
0.95	0.278	0.290	0.296
0.99	0.629	0.819	0.874

Table 2-4
Distribution For Ignition Frequency in the Upper Plenum

<u>Cumulative Probability</u>	<u>Ignition Frequency in Upper Plenum For Hydrogen Mole Fraction Ranges</u>		
	<u>H₂ mf 5.5-11%</u>	<u>H₂ mf 11-16%</u>	<u>H₂ mf >16%</u>
0.01	0.001	0.011	0.013
0.05	0.005	0.055	0.102
0.25	0.035	0.149	0.226
0.50	0.174	0.214	0.342
0.75	0.278	0.322	0.467
0.95	0.454	0.571	0.587
0.99	0.491	0.594	0.597

Table 2-5
Distribution For Ignition Frequency in the Dome

<u>Cumulative Probability</u>	<u>Ignition Frequency in Dome For Hydrogen Mole Fraction Ranges</u>		
	<u>H₂ mf 5.5-11%</u>	<u>H₂ mf 11-16%</u>	<u>H₂ mf >16%</u>
0.01	0.003	0.006	0.012
0.05	0.014	0.025	0.040
0.25	0.051	0.070	0.075
0.50	0.074	0.087	0.093
0.75	0.104	0.104	0.104
0.95	0.176	0.176	0.176
0.99	0.212	0.212	0.212

The question of flame propagation from the upper plenum to the dome was explicitly addressed only by Expert C. He believed that propagation would be assured if the concentration in the dome exceeded 4%. When considering the pressure rise associated with a concentration of 4%, the boundary of 5.5% mole fraction was considered adequate for a threshold ignition concentration in the dome. This value of 4% is quite close to the previously considered boundary of 5.5%. Thus, the APET assumes that propagation will always occur for concentrations exceeding 5.5% and will never occur for lower concentrations.

The frequency of DDT was differently assessed by all three experts. Expert A provided a distribution which applies to all mole fractions above 14%; Expert B provided a discrete probability which applies to all mole fractions above 14%, and Expert C provided a discrete probability for each of three mole fractions. Ranges were assigned to Expert C's mole fractions. Table 2-6 shows the frequency of DDT for each of three mole fraction ranges, given that an ignition has occurred

Table 2-6
Distribution For DDT

Cumulative Probability	Frequency of DDT For Hydrogen Mole Fraction Ranges		
	H ₂ mf 5.5-11%	H ₂ mf 11-16%	H ₂ mf >16%
0.01	0.10	0.50	0.50
0.05	0.10	0.50	0.50
0.25	0.10	0.50	0.50
0.50	0.50	0.60	0.80
0.75	0.65	0.65	0.90
0.95	0.94	0.94	0.94
0.99	0.99	0.99	0.99

All three experts provided distributions for impulse, given a detonation. These distributions are independent of hydrogen concentration, provided that the concentration is at least high enough for a detonation to occur. The impulse distributions are given in Table 2-7.

Table 2-7
Distribution for Detonation Impulse

Cumulative Probability	Impulsive Load (kPa-s)
0.01	2.0
0.05	2.5
0.25	4.9
0.50	10.0
0.75	12.6
0.95	22.8
0.99	43.1

Expert C provided the model for burn completeness and pressure increment as functions of initial hydrogen concentration. Table 2-8 lists pressure rises and completeness of combustion for all cases (low steam concentration in the dome), and alternate Case 2 (higher steam concentration in the dome). Burn completeness is estimated to be 100% for compartments in which a detonation occurs.

Table 2-8
Burn Completion and Pressure Rise; Cases 1, 2, 3, and 4

<u>Mole Fraction (H₂)</u>	<u>Burn Completion</u>	<u>ΔP (kPa)</u>
0.05	0.242	36
0.06	0.547	98
0.07	0.852	174
0.08	1.000	223
0.10	1.000	266

Burn Completion and Pressure Rise; Alternate Case 2

<u>Mole Fraction (H₂)</u>	<u>Burn Completion</u>	<u>ΔP (kPa)</u>
0.08	0.372	132
0.10	0.666	265
0.12	0.764	343
0.14	0.964	483

The completeness of combustion is estimated by the empirical equation to be used in the HECTR Version 2.0, developed by C. Wong.^{B-5,C-2} The equation is given by:

$$\text{Completeness} = \text{Minimum of unity or} \\ (30.499 * X_H - 1.287) * \exp(A)$$

where X_H is the hydrogen mole fraction, A is defined by:

$$A = X_S * (-4.1966 + 3.3985 * X_S)$$

and X_S is the steam mole fraction. The overpressure is determined by calculating the AICC pressure ratio and applying corrections for completeness, heat transfer to solid surfaces (factor of 5%), and adiabatic expansion into nonparticipating volumes.

Individual Elicitations for Issue 2

Expert A's Elicitation

Issue 2: Hydrogen Burn Before Vessel Breach at Sequoyah

Description of Expert A's Rationale/Methodology

Expert A reviewed relevant sequence calculations from NUREG/CR-3912,^{A-1} NUREG/CP-0056^{A-2} BMI-2104,^{A-3} IDCOR Task 23.1,^{A-4} IDCOR Task 85.5A,^{A-5} and BMI-2139.^{A-6} No calculations were available for Case 3, so a calculation of the S2D sequence from BMI-2139 was used as a proxy.

Expert A's decomposition is shown in Figure A-1. Distributions are indicated by bracketed symbols, for example [A]. From this Expert's decomposition, the probabilities of detonation in the upper plenum (Pr_{DUP}), combustion in the upper plenum without detonation (Pr_{CUP}), detonation in the ice condenser (Pr_{DIC}), and combustion in the ice condenser without detonation (Pr_{CIC}) are:

$$\begin{aligned} [Pr_{DUP}] &= (1. - [B]) * [E_{15}] * [F] \quad (\text{m.f.} \geq 0.14) \\ [Pr_{DUP}] &= 0.0 \quad (\text{m.f.} < 0.14) \\ [Pr_{CUP}] &= (1. - [B]) * [E_{ur}] * (1. - [F]) \\ [Pr_{DIC}] &= (1. - [B]) * [E_{16}] * [C] * [F] \quad (\text{m.f.} \geq 0.14) \\ [Pr_{DIC}] &= 0.0 \quad (\text{m.f.} < 0.14) \\ [Pr_{CIC}] &= (1. - [B]) * [E_{ur}] * [C] * (1. - [F]) \end{aligned}$$

A crucial point in this Expert's decomposition was whether or not the upper plenum and the dome were well mixed. Failure to mix could be explained by several upper deck doors remaining closed. If most of the upper deck doors were open, mixing was considered to be more likely. This Expert considered that the upper deck doors would probably be open, and that the probability of upper plenum mixing could not be lower than 0.5. The [B] distribution--mixing of the upper plenum and dome atmosphere--is shown in Table A-1.

If the upper plenum and dome were not mixed, the hydrogen concentrations in the upper plenum and the ice condenser were expected to be approximately the same. The [D] distribution (Table A-2) gives the mole fraction of hydrogen in the upper plenum and ice condenser by the formula:

$$MF_{H_2} = [D] * IVP * R * T / (V * P)$$

where

IVP is the in-vessel production of hydrogen,
R is the universal gas constant,
T is the temperature (assumed 560°F),
V is the volume of the upper plenum, and
P is the absolute pressure (assumed 24 psia).

Figure A-1. Expert A's Decomposition Tree. Decomposition for Hydrogen Burn.

The frequency of ignition in the upper plenum is $[E_{mf}]$, where mf is the mole fraction of hydrogen in the (unmixed) upper plenum. Separate distributions are used for mole fractions of 0.06 to 0.10 $[E_{.08}]$, 0.10 to 0.14 $[E_{.12}]$, and mole fractions greater than 0.14 $[E_{.16}]$. The distributions for $[E_{.08}]$, $[E_{.12}]$, and $[E_{.16}]$ are shown in Table A-3.

Table A-1
Distribution for Mixing of Upper Plenum
and Dome; [B] Distribution

<u>Cumulative Probability</u>	<u>[B] Distribution</u>
0.01	0.5
0.25	0.7
0.50	0.8
0.75	0.9
0.99	1.0

Table A-2
Distribution for Mole Fraction in Unmixed
Upper Plenum; [D] Distribution

<u>Cumulative Probability</u>	<u>[D] Distribution</u>
0.01	0.04
0.25	0.06
0.50	0.07
0.75	0.075
0.99	0.08

Table A-3
Distribution for Frequency of Ignition in the Upper Plenum
[E_{.05}], [E_{.12}] and [E_{.16}] Distributions

<u>Cumulative Probability</u>	<u>[E_{.05}] Dist.</u>	<u>[E_{.12}] Dist.</u>	<u>[E_{.16}] Dist.</u>
0.01	0.00	0.05	0.15
0.25	0.01	0.12	0.33
0.50	0.02	0.16	0.38
0.75	0.05	0.20	0.41
0.99	0.09	0.29	0.53

The Expert explained that the energy had to be delivered in a very short time, with very high spatial density, even though the total energy requirements were quite low. Considering the requirements for rapid energy delivery and high energy density, this Expert selected relatively low values for frequency of ignition; the maximum possible frequency of detonation was estimated to be 0.5. Leaner mixtures require more energy for detonation, so that the frequency of detonation has to be reduced for lower mole fractions.

This Expert considered that if ignition sources were present at all, they were more likely to be in the upper plenum than in the ice condenser. The reduced probability of ignition in the ice condenser was handled by multiplying the [E] distributions for frequency of ignition in the upper plenum by the [C] distribution, which is always less than 0.5 (Table A-4).

If ignition occurs, detonation is only considered possible if the hydrogen mole fraction exceeds 0.14. The probability that a combustion event is a detonation, given mole fractions greater than 0.14, is given by the [F] distribution (Table A-5). For mole fractions less than 0.14, every combustion event is a deflagration.

If combustion is a deflagration, the peak pressures are functions of mole fraction of hydrogen. Pressures for deflagrations in the ice condenser or upper plenum are given by the [Gmf] distributions in Table A-6. Because detonation can only occur for mole fractions exceeding 0.14, impulses are not functions of concentration. Impulses are given by the [H] function in Table A-7.

Mass of Remaining Hydrogen

The mass of hydrogen released from the RCS is $IVP \cdot [I]$, where IVP is the total in-vessel hydrogen production, and the [I] distribution is given in Table A-8. Values in this table are based principally on MAAP calculations, except for the upper ends of the distributions. The fraction of in-vessel production released to the upper plenum or dome is given by $[A] \cdot IVP$, where the [A] distribution is shown in Table A-9. The mass of hydrogen delivered to the ice condenser was estimated by the method described in the general discussion. Expert A considered that burning, if it occurred, would be complete, or nearly so.

Expert A did not provide [I] and [A] distributions for Case 4. The distributions for Case 3 represent high fractions of hydrogen released, and Case 3 is expected to be physically similar to Case 4. Therefore, Case 3 distributions are used as a proxy for Case 4.

Table A-4
Distribution for Frequency of Ignition
in Ice Condenser Relative to Frequency
in Upper Plenum; [C] Distribution

<u>Cumulative Probability</u>	<u>[C] Distribution</u>
0.01	0.10
0.25	0.30
0.50	0.40
0.75	0.45
0.99	0.50

Table A-5
Distribution for Frequency of Detonation
in Ice Condenser or Upper Plenum, Given Ignition;
[F] Distribution

<u>Cumulative Probability</u>	<u>[F] Distribution</u>
0.01	0.50
0.25	0.65
0.50	0.80
0.75	0.90
0.99	1.00

Table A-6
Distribution for Peak Pressure, Given
Deflagration in IC or UP; [G_{mf}] Distribution

<u>Cumulative Probability</u>	<u>G₀₈ (kPa)</u>
0.01	145
0.25	152
0.50	160
0.75	170
0.99	180

<u>Cumulative Probability</u>	<u>G₁₂ (kPa)</u>
0.01	160
0.25	170
0.50	180
0.75	190
0.99	200

Table A-6 (continued)

<u>Cumulative Probability</u>	<u>G_{16} (kPa)</u>
0.01	180
0.25	190
0.50	200
0.75	205
0.99	210

Table A-7
Distribution for Impulse, Given Detonation;
[H] Distribution

<u>Cumulative Probability</u>	<u>[H] Distribution (k Pa-s)</u>
0.01	2
0.25	3
0.50	4
0.75	5
0.99	15

Table A-8
Distribution for Fraction of H_2 Released
from RCS; [I] Distribution

<u>Cumulative Probability</u>	<u>[I] (Case 1)</u>
0.01	0.30
0.25	0.55
0.50	0.70
0.75	0.75
0.99	0.80

<u>Cumulative Probability</u>	<u>[I] (Case 2)</u>
0.01	0.40
0.25	0.60
0.50	0.70
0.75	0.75
0.99	0.80

Table A-8 (continued)

<u>Cumulative Probability</u>	<u>[I] (Case 3)</u>
0.01	0.60
0.25	0.65
0.50	0.70
0.75	0.75
0.99	0.80

Table A-9
Distribution for Fraction of H₂ Released
to Dome/Upper Plenum; [A] Distribution

<u>Cumulative Probability</u>	<u>[A] (Case 1)</u>
0.01	0.08
0.25	0.095
0.50	0.11
0.75	0.12
0.99	0.13

<u>Cumulative Probability</u>	<u>[A] (Case 2)</u>
0.01	0.10
0.25	0.12
0.50	0.14
0.75	0.15
0.99	0.16

<u>Cumulative Probability</u>	<u>[A] (Case 3)</u>
0.01	0.12
0.25	0.15
0.50	0.17
0.75	0.185
0.99	0.20

Results of Expert A's Elicitation

Expert A's logic tree was programmed and evaluated using a Monte Carlo method ($N = 1000$). By the Kolmogoroff-Smirnoff test, the Monte Carlo distribution does not differ from the "true" distribution by more than 0.039. A solution was carried out for each case and for both 25% and 60% zirconium oxidation. Impulses in the ice condenser and upper plenum were found to differ only trivially by case and fraction oxidized. This Expert only had deflagrations occurring in the ice condenser and upper plenum. The pressures are uniformly low and pose no threat to containment and will not be used in the final aggregation.

As a check on the distributions, consider combination of the median values. The probability of detonation in the ice condenser is $(1.-B)*E_{14}*C*F$, where the symbols B, E, C, and F indicate the median values of the [B], [E], [C], and [F] distributions.

$P_{DICEdetn} = (1.-0.8)(0.35)*(0.4)*(0.8) = 0.0224$; hence, the probability of no detonation is 0.9776. The median impulse is 8 kPa-s, and the probability of an impulse less than this, given that a detonation occurs, is 0.5. Therefore, the unconditional probability of an impulse less than 8 kPa-s is $1.-(0.5)(.0224) = .9888$. The probability that the impulse is less than 8 kPa-s is slightly greater than 0.99, or very close to the value calculated from the medians of the individual distributions.

Sources of Uncertainty

Expert A assigned the greatest uncertainty to the mixing of the upper plenum and dome, although considerable uncertainty was also assigned to the probability of ignition. If the dome and upper plenum are well mixed, combustion was not considered credible. He believed that combustion of hydrogen in the dome was not credible, given the amounts of hydrogen production generally believed possible. The conclusion that combustion in the dome was impossible was based on MAAP calculations, which indicate only a fraction of the hydrogen released from the RCS before vessel breach. The amount available for mixing into the dome atmosphere would be too small for combustible concentrations in the dome, or in the upper plenum if the plenum and dome were well mixed. If a station blackout with core meltdown occurred at Sequoyah, and the dome was known to have failed by overpressure due to a hydrogen burn before vessel breach, Expert A would say that production of hydrogen must have exceeded any current estimate. Consequently, Expert A did not provide a distribution for pressure rise in containment due to a hydrogen deflagration in the dome.

REFERENCES

- A-1. A. L. Camp, V. L. Behr, and F. E. Haskin, "MARCH-HECTR Analysis of Selected Accidents in an Ice-Condenser Containment," Sandia National Laboratories, NUREG/CR-3912, SAND83-0501, December 1984.
- A-2. F. Haskin et al., "HECTR Results for Ice Condenser Containment Standard Problem," Proceedings of the Second Workshop on Containment Integrity, Crystal City, VA, NUREG/CP-0056, SAND84-1514, August 1984.
- A-3. J. A. Gieseke et al., "Radionuclide Release Under Specific LWR Accident Conditions," Volume IV: PWR Ice Condenser Design, Battelle Columbus Division, BMI-2104, 1984.
- A-4. Industry Degraded Core Rulemaking Program (IDCOR), "Sequoyah Nuclear Plant Integrated Containment Analysis, IDCOR Task 23.1," Technical Tennessee Valley Authority, Nuclear Engineering Branch, Report 23.1, July 1984.
- A-5. Industry Degraded Core Rulemaking Program (IDCOR), "Sequoyah Nuclear Plant Integrated Containment Analysis, IDCOR Task 85.5A," Tennessee Valley Authority, Nuclear Engineering Branch, Technical Report 85.5A, July 1984.
- A-6. R. S. Denning et al., "Supplemental Radionuclide Release Calculations for Selected Severe Accident Sequences," Battelle Columbus Division, NUREG/CR-4624, BMI-2139, 1986.

Expert B's Elicitation

Hydrogen Burn Before Vessel Breach at Sequoyah

Description of Expert B's Rationale/Methodology

Expert B reviewed calculations from NUREG/CR-3912,^{B-1} SAND85-1824C,^{B-2} Haskin et al.,^{B-3} and IDCOR Task 23.1.^{B-4} However, he placed the greatest reliance on References B-1 and B-2.

Expert B provided a decomposition tree shown in Figure B-1. The simplified logic of the tree is that the necessary conditions for combustion would be that an ignition source must be available; that it must be in the ice condenser, upper plenum, or dome; and that the gas mix in the compartment where the ignition source occurs must be flammable or detonable.

Expert B did not distinguish between cases; however, the decomposition is somewhat different for low and high zirconium oxidation levels. Figure B-1 shows this Expert's decomposition. Distributions are indicated by bracketed symbols, for example [A]. From the decomposition, the probabilities of combustion in the dome (Pr_{CD}), combustion in the upper plenum (Pr_{CUP}), combustion in the ice condenser (Pr_{CIC}), and detonation in the ice condenser (Pr_{DIC}) are:

$Pr_{CD} = 0$. (25% zirconium oxidation)

$Pr_{CD} = [A] * [B_D] * (1 - C_D)$ (60% zirconium oxidation)

$Pr_{CUP} = [A] * [B_{UP}] * (1 - C_{UP})$ (25% and 60% zirconium oxidation)

$Pr_{CIC} = [A] * [B_{IC}] * (1 - C_{IC}) * D_{IC}$ (25% and 60% zirconium oxidation)

$Pr_{DIC} = [A] * [B_{IC}] * (1 - C_{IC}) * (1 - D_{IC})$ (25% and 60% zirconium oxidation).

Results of Expert B's Elicitation

Expert B's decomposition tree was programmed and solved by a Monte Carlo method (N = 1000).

Impulse and Pressure

The most crucial points in Expert B's decomposition were the existence of an ignition source and its location, and most of the uncertainty in the probabilities of combustion and detonation are assigned to the uncertainties of ignition. The existence of an ignition source, is represented by distribution [A], a normal distribution with a mean of 0.50 and a standard deviation of 0.1216. Distribution [A] is provided in Table B-1. The assessment of the location of the ignition source is provided by the $[B_D]$, $[B_{UP}]$, and $[B_{IC}]$ distributions, which are shown in Table B-2. The final convolved distributions for ignition in each of the locations independent of concentration is provided in Table B-3.

<u>Cumulative</u> <u>Probability</u>	<u>AI Distribution</u>
0.05	0.3
0.50	0.5
0.95	0.7

Table B-2
Distributions for Probability of Ignition Location
[B_D], [B_{UP}] and [B_{IC}] Distributions

Cumulative Probability	Probability That Ignition Occurs in:		
	<u>Dome</u>	<u>Upper Plenum</u>	<u>Ice Condenser</u>
	<u>[B_D] Dist.</u>	<u>[B_{UP}] Dist.</u>	<u>[B_{IC}] Dist.</u>
0.05	0.33	0.33	0.33
0.50	0.22	0.44	0.33
0.95	0.14	0.57	0.29

Table B-3
Distributions for Ignition Frequency

<u>Cumulative Probability</u>	<u>Ice Condenser</u>	<u>Upper Plenum</u>	<u>Dome</u>
0.01	0.075	0.097	0.046
0.05	0.094	0.122	0.063
0.25	0.139	0.181	0.076
0.50	0.158	0.219	0.104
0.75	0.196	0.261	0.152
0.95	0.233	0.324	0.183
0.99	0.254	0.361	0.222

Expert B assessed flammability by observing the calculated gas composition over a 1000-s time period. The fraction of time that the mixture was in the flammable regime was taken to be the probability that the mixture was flammable at any time. The flammability is quantified in the variables, C_D, C_{UP}, and C_{IC} as expressed for the different zirconium oxidation levels in Table B-4.

Table B-4
Probability of Flammability

<u>Location</u>	<u>Variable</u>	<u>25% Zr Oxid.</u>	<u>60% Zr Oxid.</u>
Dome	C _D	0.00	0.20
Upper Plenum	C _{UP}	0.20	0.20
Ice Condenser	C _{IC}	0.75	0.75

Detonability was considered possible only in the ice condenser and was addressed in the same manner as flammability. Given ignition of a flammable mixture in the ice condenser, the mixture is detonable and will transition from deflagration to detonation 50% of the time. Thus, the value of D_{IC} is 0.50. The impulse distribution conditional on occurrence of a detonation is shown in Table B-5. Expert B did not expect impulse to be a function of the fraction of zirconium oxidized, as long as at least 15% was oxidized.

Table B-5
Distribution for Detonation Impulse

<u>Cumulative Probability</u>	<u>Impulsive Load (kPa-s)</u>
0.05	8.0
0.25	11.0
0.50	12.0
0.75	13.0
0.90	14.0
0.95	14.5

Expert B agreed to use the model for pressure rise due to a deflagration in the dome that was provided by Expert C. The model utilizes the AICC pressure ratio, with corrections made for burn completeness, heat transfer to solid surfaces, and adiabatic expansion into nonparticipating volumes. Pressures in the ice condenser and upper plenum lie considerably below the distributions from the structural experts panel for containment failure.

Mass of Hydrogen Burned

Expert B did not give distributions for the masses of hydrogen in each compartment. The method described in the description of method of aggregation for estimating mole fractions in each compartment was used. Expert B indicated that burn completion was to be estimated using the model of Wong.^{B-5} The burn completion model applied for conditions of no steam in containment and no fans operating is summarized in Table B-6. The mass burned in any compartment is the product of the burn completion and the mass of hydrogen in the compartment, given sufficient oxygen for the burn.

Expert B did not distinguish between cases. However, hydrogen concentrations were required for calculation of hydrogen burned fraction, and Expert B agreed to use Expert A's distributions for hydrogen released from the RCS and to the upper plenum and dome, as provided in Tables B-7 and B-8.

Table B-6
Burn Completion

<u>Mole Fraction (H₂)</u>	<u>Burn Fraction</u>
0.04	0.00
0.05	0.24
0.06	0.55
0.07	0.85
0.08	1.00
0.10	1.00

Table B-7
Distributions for Fraction of Hydrogen
Released From RCS

<u>Case</u>	<u>Fractile</u>				
	<u>0.01</u>	<u>0.25</u>	<u>0.50</u>	<u>0.75</u>	<u>0.99</u>
1	0.30	0.55	0.70	0.75	0.80
2	0.40	0.60	0.70	0.75	0.80
3	0.60	0.65	0.70	0.75	0.80

Table B-8
Distributions for Fraction of Hydrogen to
Upper Plenum and Dome

<u>Case</u>	<u>Fractile</u>				
	<u>0.01</u>	<u>0.25</u>	<u>0.50</u>	<u>0.75</u>	<u>0.99</u>
1	0.08	0.095	0.11	0.12	0.13
2	0.10	0.12	0.14	0.15	0.16
3	0.12	0.15	0.17	0.185	0.20

Sources of Uncertainty

Major sources of uncertainty are the existence and location of an ignition source. Additional uncertainty has been introduced by the use of Expert A's distributions for fractions of hydrogen released from the RCS. Uncertainties were also assigned to the peak impulse, given that a detonation occurred.

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- B-1. A. L. Camp, V. L. Behr, and F. E. Haskin, "MARCH-HECTR Analysis of Selected Accidents in an Ice-Condenser Containment," Sandia National Laboratories, NUREG/CR-3912, SAND83-0501, December 1984.
- B-2. S. E. Dingman and A. L. Camp, "Pressure-Temperature Response in an Ice-Condenser Containment for Selected Accidents," Trans. 13th Water Reactor Safety Information Meeting, SAND85-1824C, NUREG/CP-0071, Gaithersburg, MD, 1985.
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Expert C's Elicitation

Hydrogen Burn Before Vessel Breach at Sequoyah

Description of Expert C's Rationale/Methodology

Expert C used References C-1 through C-9 for purposes of this elicitation. The attached papers titled "Possibility of Detonation and Other Containment Loads for Sequoyah" (Attachment A) and "Additional Material for Sequoyah Elicitation" (Attachment B) by Expert C, present much of the rationale for the quantification of this issue. However, Expert C was unable to predict the concentrations of hydrogen in the various compartments; the method described in the description of method of aggregation was used.

Expert C considered presence of an ignition source to be the essential uncertainty for this issue, because code calculations predict detonable mixtures within the ice condenser for appreciable periods during this sequence (if igniters and fans are operating, hydrogen is never a problem). The possible ignition sources were evaluated and it was decided that slamming of the metal intermediate deck doors is the most likely ignition source. The upper deck doors can flop over so that they remain open, but the upper deck doors are designed to stop by colliding into each other.

Expert C considered combustion in both the ice condenser and the dome. The concentration in the dome would only be flammable for the highest level of in-vessel hydrogen production, and only towards the end of the accident. The ice condenser would have been detonable for long periods by this time, and thus would have had much more chance of a damaging combustion. Consequently, Expert C gave a rather low likelihood for combustion in the dome.

Deflagrations would be of importance only if they occurred in the dome. The amount of hydrogen in the ice condenser or upper plenum is too small to be of any consequence for deflagration. Expert C therefore restricted the focus to events which would lead to detonation in the ice condenser or deflagration in the dome.

Results of Expert C's Elicitation

Impulse and Pressure

Cases 1, 3, and 4

Expert C's decomposition is shown in Figure C-1. This Expert estimated the probability of a path being open to the dome at 0.1, based on the likelihood of intermediate deck doors being stuck open. If the doors were stuck open, the frequency of ignition in the ice condenser, upper plenum, and dome are shown by $[C_{IC}]$, $[C_{UP}]$, and $[C_D]$ on Figure C-1. Expert C gave "half-lives" to ignition (the times at which an ignition frequency of 0.5 would be expected) as shown in Table C-1. The times of interest range up to about 50 minutes. It is assumed that any time within this interval is equally interesting. The Expert estimated the maximum frequencies of

Figure C-1. Expert C's Decomposition Tree.

Table C-1
Half-Lives for Ignition

<u>Mole Fraction H₂</u>	<u>Ignition Half-Life</u>
5 to 12%	20 minutes
12 to 18%	10 minutes
18 to 45%	5 minutes

ignition to be 0.3, 0.6, and 0.1 in the ice condenser, upper plenum, and dome, respectively. It should be understood that ignition initiated in the dome is only of interest if there has been no previous ignition in the ice condenser or upper plenum. A combustion in the upper plenum whether detonation or deflagration--would spread to the dome if the dome mole fraction were greater than 0.04.

The probability of a clear path was estimated to be 0.1. In the more likely event that the path was not open to the dome, frequency of ignition in the ice condenser and upper plenum are shown by $[D_{IC}]$ and $[D_{UP}]$ on Figure C-1. Expert C estimated that the maximum frequency of ignition in the ice condenser and upper plenum in this case would be 0.90 and 0.05, respectively. A combustion in the ice condenser would spread to the upper plenum if the mole fraction of hydrogen in the upper plenum were greater than 10%.

The ignition frequency distributions for each compartment for the two cases (open/unopen path) described above can be resolved when the relative frequency of the cases is incorporated into the model. The resulting ignition frequency distributions are provided in Tables C-2 through C-4.

Table C-2
Distribution for Ignition Frequency
in the Ice Condenser

Cumulative Probability	Ignition Frequency in Ice Condenser For Hydrogen Mole Fraction Ranges		
	H_2 mf 5.5-11%	H_2 mf 11-16%	H_2 mf >16%
0.01	0.005	0.010	0.021
0.05	0.026	0.051	0.093
0.25	0.109	0.177	0.251
0.50	0.177	0.233	0.270
0.75	0.249	0.274	0.288
0.95	0.519	0.716	0.857
0.99	0.712	0.873	0.891

Table C-3
Distribution for Ignition Frequency
in the Upper Plenum

<u>Cumulative Probability</u>	<u>Ignition Frequency in Upper Plenum For Hydrogen Mole Fraction Ranges</u>		
	<u>H₂ mf 5.5-11%</u>	<u>H₂ mf 11-16%</u>	<u>H₂ mf >16%</u>
0.01	0.003	0.004	0.005
0.05	0.017	0.020	0.023
0.25	0.147	0.260	0.408
0.50	0.319	0.464	0.557
0.75	0.424	0.551	0.578
0.95	0.485	0.590	0.596
0.99	0.497	0.598	0.599

Table C-4
Distribution for Ignition Frequency
in the Dome

<u>Cumulative Probability</u>	<u>Ignition Frequency in Upper Plenum For Hydrogen Mole Fraction Ranges</u>		
	<u>H₂ mf 5.5-11%</u>	<u>H₂ mf 11-16%</u>	<u>H₂ mf >16%</u>
0.01	0.001	0.003	0.006
0.05	0.007	0.014	0.025
0.25	0.030	0.047	0.068
0.50	0.053	0.078	0.092
0.75	0.071	0.092	0.096
0.95	0.083	0.098	0.099
0.99	0.090	0.100	0.100

The probability of a DDT as a function of hydrogen mole fraction, is shown in Table C-5. This was fitted as a log-normal distribution with median at 0.1833 mole fraction, and 10th and 90th percentiles at 0.14 and 0.24 mole fractions, respectively. The probability of a DDT for times of either an open or unopen path to the dome is the same.

If a detonation occurs in the ice condenser or upper plenum, the magnitude of the impulse is given by the distribution of Table C-6; this was fitted by a log-normal distribution with a median at 12 kPa-s, and 10th and 90th percentiles at 6 and 24 kPa-s. The impulse distributions differ only in unimportant details between 25% and 60% zirconium oxidation. If a deflagration occurs in the dome, or if combustion spreads to the dome, the pressures in the dome are given by Table C-7.

Table C-5
Deflagration-to-Detonation Transition

<u>Mole Fraction H₂</u>	<u>Probability of DDT</u>
14%	0.1
18%	0.6
24%	0.9

Table C-6
Distribution for Impulse, Given Detonation

<u>Impulse (kPa·s)</u>	<u>Relative Likelihood</u>
3	0.05
6	0.50
12	1.00
24	0.50
36	0.20
48	0.05

Table C-7
Pressure in Dome, Ice Condenser Not Bypassed
(Cases 1, 2, 3, and 4)

<u>Mole Fraction H₂</u>	<u>Pressure in Dome, kPa</u>
0.05	50
0.06	113
0.07	189
0.08	238
0.10	281

Case 2

Expert C cited a CONTAIN calculation which indicated that most of the steam and hydrogen would pass directly to the upper containment via a drain line in the refueling canal, largely bypassing the ice condenser. If this happens, there would be no possibility of detonation or deflagration in the ice condenser or upper plenum, although deflagration is still possible in the dome. Table C-8 shows pressures from a deflagration in the upper compartment as a function of mole fraction, including the effects of the high steam fraction expected in the dome if the ice condenser is bypassed. Only the single CONTAIN calculation exists for this case, and the behavior of the steam and hydrogen is highly uncertain. Therefore, for Case 2, bypass of the ice condenser and passage through the ice condenser (as in Cases 1, 3, and 4) are considered to be equally likely.

Table C-8
Pressure in Dome, Ice Condenser Bypassed
(Alternate Case 2)

<u>Mole Fraction H₂</u>	<u>Pressure in Dome, kPa</u>
0.08	117
0.10	260
0.12	338
0.14	478

Distribution of Hydrogen in Containment

Expert C provided data on the fraction of hydrogen released from the RCS that is in each compartment before vessel breach. The data were obtained from the HECTR calculations^{C-1} and the CONTAIN calculation. For no ice bypass, the amount of hydrogen in the dome in the clear path case was assumed to be 100% of the amount predicted by HECTR calculations reported in Table C-9. The amount in the case with no bypass of ice and the absence of a clear path, was estimated to be 50% of the amount predicted. The 50% which is not admitted to the dome, is distributed through the remaining compartments in the same ratios as were predicted by HECTR. Table C-9 shows the fraction of hydrogen in each compartment.

Table C-9
Distribution of Hydrogen in Containment; Compartmental Fraction of Total
Hydrogen Released from the RCS

<u>Compartment</u>	<u>HECTR Prediction (Cases 1, 2, 3, and 4)</u>	<u>CONTAIN Prediction (Alternate Case 2)</u>
Lower Compartment	0.35	0.44
Ice Condenser	0.36	0.13
Upper Plenum of Ice Condenser	0.03	0.01
Upper Compartment	0.26	0.42

Mass of Hydrogen Burned

The mass of hydrogen in each compartment was estimated as described in the general discussion. Expert C specified that the completeness of combustion should be estimated by the empirical equation to be used in the HECTR Version 2.0, developed by C. Wong.^{C-2} Burn completion as a function of mole fraction is given in Table C-10 for Cases 1, 2, 3, and 4, and in Table C-11 for alternate Case 2 with the ice condenser bypassed.

Table C-10
Burn Completeness, Ice Condenser Not Bypassed
(Cases 1, 2, 3, and 4)

<u>Mole Fraction H₂</u>	<u>Burn Completeness</u>
0.05	.242
0.06	.547
0.07	.852
0.08	1.000

Table C-11
Burn Completeness, Ice Condenser Bypassed
(Alternate Case 2)

<u>Mole Fraction H₂</u>	<u>Burn Completeness</u>
0.08	.372
0.10	.666
0.12	.764
0.14	.960

Sources of Uncertainty

Expert C assigned the major source of uncertainty to the existence and timing of an ignition source. This Expert believed that the atmosphere in the ice condenser would eventually detonate if there were enough time. The principal uncertainty is whether there is enough time to be sure that an ignition source is present while the ice condenser atmosphere is detonable. The probability of a DDT is a function of hydrogen concentration, so that uncertainties in the production, release, and distribution of hydrogen also impact the uncertainty. The magnitude of impulse resulting from a detonation is also highly uncertain.

Suggested Methods for Reducing Uncertainty

One source of uncertainty is the likelihood of bypass of the ice condenser in Case 2. More extensive calculations of the very small leak scenario, and a better understanding of the paths for bypass, would help to reduce the uncertainty in Case 2.

The greatest source of uncertainty is in the probability of ignition. Expert C does not believe that experiments could be meaningfully pursued at this time, because the important parameters are not known. This Expert suggests a literature search--which should not be confined to the literature specific to nuclear power--to help delineate current understanding of

random ignition processes. The literature search would take about six months. After available knowledge has been summarized, an experimental or theoretical program might be justified.

REFERENCES

- C-1. A. L. Camp, V. L. Behr, and F. E. Haskin, "MARCH-HECTR Analysis of Selected Accidents in an Ice-Condenser Containment," Sandia National Laboratories, NUREG/CR-3912, SAND83-0501, December 1984.
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- C-9. M. P. Sherman, S. R. Tieszen and W. B. Benedick, "Flame Acceleration and Transition to Detonation in Channels," Sandia National Laboratories, SAND87-1444C, 1987.

POSSIBILITY OF DETONATION AND OTHER CONTAINMENT LOADS FOR SEQUOYAH

February 23, 1988

Several members of the containment loads expert panel including myself have been asked to examine the possible loads due to hydrogen combustion in the Sequoyah plant prior to vessel breach for several station blackout type accidents [1]. The two large air return fans between the upper and lower compartments are not operating, the deliberate ignition system is not operating, and the upper compartment sprays are not operating. These cases are: a TMLB', a seal LOCA (S₁) high pressure meltdown, a station blackout with a stuck open PORV (S₂) LOCA, and a station blackout with cycling PORV and a subsequent induced large hot leg failure. The panel agreed to consider two levels of zirconium oxidation, 25% is the low level and 80% is the high level. The purpose of this memorandum is to document my thinking on the subject, and possibly help the other members working on the issue.

The following table gives useful values of volumes, masses and moles for Sequoyah. The volumes are taken from computer input to Ref. 2; the Zirconium mass was taken from a study by C. C. Wong, Sandia Div. 6427. The number of kmoles of air were obtained from the perfect gas law ($N = PV/RT$) using $P = 101$ kPa, $T = 298$ K, $V = 33,740$ m³, and $R = 8.317$ kJ/kmole-K

<u>Region</u>	<u>Volume, m³</u>	<u>Percent Total</u>
lower compartment	= 8184	24.3
dead-ended region	= 2662	7.9
lower plenum	= 685	2.0
ice condenser	= 2444	7.2
upper plenum	= 1330	3.9
upper compartment	= 18435	54.6
total	= 33740	

mass Zirconium	= 51,000 lb = 23,133 kg
kmole Zr.	= 253.6 kmole
kmole H ₂ (100% oxidation)	= 507.2 kmole
mass H ₂ (100% oxidation)	= 1022 kg

kmole air in containment	= 1375 kmole
kmole of O ₂ in containment	= 287 kmole

In the examination of Refs. 2,3 together with the computer printout used in these studies, certain general features common to all these accidents became clear. These features cause the desired results to be insensitive to many of the assumptions

used. In the following sections we address the common features of these accidents and the differences between them.

The lack of return air fan operation dominates the conditions in containment prior to the first hydrogen burn. With fans operating, the hydrogen mole fractions in the various compartments tend to be similar. There are no detonable mixtures. Deflagrations tend to be global. Deliberate ignition is then very important in preventing the buildup of hydrogen. As long as the ice condenser functions to condense most of the steam, and the small area bypass from the lower to upper compartment in the refueling channel is not significant, the containment sprays in the upper compartment do not alter conditions much. Without the return air fans, conditions are totally different as discussed in the following paragraphs.

The lower compartment is inerted due to the low level of oxygen (typically ~ 1%) and the high level of steam (usually over inerting level ~ 55%). This is true in all accidents in which the initial release of steam from the primary system drives the air from the lower compartment. Consequently, there appears to be no chance of a diffusion flame at the hydrogen source. Condensation of steam in the lower compartment is not important once the surface temperatures go above the dew point. Consequently, conditions in the lower compartment tend to be insensitive to the rates of steam and hydrogen release, but sensitive only to the total amounts.

There are dead-ended regions off the lower compartment such as the pressurizer dog house. The gas mixture in these regions can be combustible, and burns are predicted there in several cases. However, these burns are of little importance. Deflagrations in these regions can not propagate into the lower compartment. The volumes involved are not large enough to give rise to significant pressure rises in containment. Detonable mixtures are not predicted for these regions. Even if a detonation did occur in the pressurizer dog house, the impulse on the containment wall would not be great.

In order to have a large pressure rise due to a deflagration, there must be a nearly simultaneous deflagration in a large fraction of containment. This requires that a deflagration occur in the upper compartment, although the deflagration may have originated elsewhere. Unless there is significant bypassing of the ice condenser, little steam is convected into the upper compartment. With the condensation of steam in the ice condenser, HECTR results predict hydrogen is convected slowly into the upper compartment. In many accident scenarios, the hydrogen mole fraction in the upper compartment never exceeds the flammability limit. In cases where an upper compartment burn is

predicted, large pressure spikes accompany these burns. Consequently, the issue of the maximum overpressure predicted in Sequoyah due to hydrogen deflagration is largely dependent on the assessment of the possibility of an upper compartment deflagration. The upper compartment gas mixture never approaches a possible detonable mixture. If the steam-hydrogen release rate is very low as in an S₁HF case, it may be that most of the flow from the lower to upper compartment is by the refueling pit bypass opening and not by the ice condenser. In this case high steam concentrations are possible in the upper compartment. A preliminary calculation with the CONTAIN code indicates the upper compartment atmosphere could get to 45% steam, 8% hydrogen. This mixture is just inside the flammability limit.

In all cases considered by HECTR, the steam concentration in the ice condenser is low and the hydrogen concentration reaches detonable values. For an S₁HF case considered in Ref. 3 the composition was 25.9% hydrogen, 0.38% steam, 14.7% oxygen, and the rest nitrogen. Using a pressure of 130 kPa and a temperature of 283 K, the Shepherd ZND computer code [4] was run by S. E. Slezak to obtain a detonation cell width of 20.1 mm. In the study of Sherman and Berman [4] hydrogen-air-steam mixtures were classified as to detonability in five classes. Mixtures with detonation cell widths up to 20 mm were classified as extremely detonable, class 1. Consequently, the mixture considered is on the border of class 1 and class 2, where class 2 is easily detonable. The geometry of the surroundings was classified by its flame acceleration potential into five classes. The ice condenser geometry is considered class 2, promotes flame acceleration, by Sherman. Berman considered it class 1. He felt that in downward flame propagation, the flame would be forced sideways going around the ice baskets and generating turbulence. Sherman considered it class 2, because although there are many obstacles to promote flame acceleration in a circumferential burn, there is transverse venting upward. The mixture class and the geometric class are used to give a results class for the possibility of deflagration-to-detonation transition (DDT). For mixture class 1 and geometric class 1 or 2, the results class is 1, "DDT is highly likely." For Geometric class 2 and mixture class 2, the result class is 2, "DDT is likely." In many other cases the hydrogen concentration is about 22%, with steam concentrations of one or two percent. This would increase the detonation cell width about 30% from the previous case, slightly reducing the detonability of the mixture and putting the results into class 2, "DDT is likely."

In the ice condenser upper plenum, little steam enters by convection from the ice condenser below. The hydrogen concentrations are much lower than in the ice condenser. In all cases, the mixtures are flammable, but in many, the hydrogen mole

fraction is below the 9% downward flammability limit. It is an interesting question if the igniters in the upper plenum operate if the flame can propagate into the ice condenser. The flows generated by the combustion may cause some hot section of gases to move downward and ignite the gas in the ice condenser, even if the mixture is nominally outside the downward flammability limit.

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April 1, 1988

Additional Material for Sequoyah Elicitation

We consider the pressure rise due to deflagration in the Sequoyah upper compartment for the case of no steam and 40% steam. The upward flammability limits for hydrogen-air-steam mixtures can be estimated by the empirical equation of Marshall [1].

$$\% \text{Steam} = 100. - \% \text{H}_2 - 37.3 \cdot \exp(-0.007 \cdot \% \text{H}_2) - 518.0 \cdot \exp(-0.488 \cdot \% \text{H}_2)$$

The above gives the following results:

<u>Hydrogen Mole Fraction</u>	<u>Steam Mole Fraction</u>
.0444	.000
.05	.138
.06	.305
.0694	.400
.07	.404

The completeness of combustion is estimated by the empirical equation to be used in HECTR Version 2.0 developed by C. C. Wong. The correlation of experiment data is for a quiescent case (no sprays or fans), and for a turbulent case (sprays and/or fans).

$$\text{Completeness (quiescent)} = \text{Minimum of unity or } (30.499 X_H - 1.2827) \cdot \exp(A)$$

where X_H is the hydrogen mole fraction, X_s is the steam mole fraction, and

$$A = X_s \cdot (-4.1966 + 3.3985 \cdot X_s)$$

For the turbulent case,

$$\text{Completeness (turbulent)} = \text{Minimum of unity or } (28.638 \cdot X_H - 1.0463) \cdot \exp(A)$$

The results are

<u>Steam Mole Fr.</u>	<u>Hydrogen Mole Fr.</u>	<u>Completeness</u>	
		<u>Quiescent</u>	<u>Turbulent</u>
0.0	.08	1.00	1.00
	.07	.852	.958
	.06	.547	.672
	.05	.242	.386
	.045	.090	.242
0.4	.15	1.00	1.00
	.14	.960	.952
	.12	.764	.768
	.10	.666	.676
	.08	.372	.400
	.0694	.268	.303

The estimated deflagration pressures will be determined as follows. The initial pressure and temperature of the mixtures will be estimated. The pressure ratios for the no steam case, and the pressure for the steam case will be determined from the plots submitted by Sherman to the structural and the loads groups [2]. The pressure ratio or overpressure will be reduced by multiplication by the completeness. The overpressures will be assumed to be reduced by 5% for heat transfer to solid surfaces losses. Finally the pressure reduction due to expansion into the lower compartment will be estimated.

The correction for expansion into the lower compartment is based on isentropic expansion from the upper into the lower compartment until the pressure is balanced. This type analysis was done in the memorandum for Grand Gulf. About 1/4 of the total volume is in the ice condenser, upper and lower plenum. These volumes must be considered as part of the combustion volume, part of the volume for expansion, or as isolated. If V_1 is the volume of the volume that has combustion, P_1 the corresponding constant volume pressure, V_2 the volume into which gas will expand (lower compartment volume, etc.), P_2 the corresponding constant volume pressure, ΔV the increase in combustion gas volume due to expansion into V_2 , and P_3 the equilibrated pressure after this expansion, we have

$$\Delta V/V_2 = [(P_1/P_2)^{(1/\gamma)} - 1] / [(V_2/V_1) + (P_1/P_2)^{(1/\gamma)}]$$

$$P_3/P_1 = 1/[1 + \Delta V/V_1]^\gamma$$

NO STEAM CASE

The temperature in the upper compartment will be near normal. The pressure will be increased because of the steam present in the lower compartment and the hydrogen. For simplicity, assume a pressure of 1.5 Bar independent of the hydrogen mole fraction, and combustion in all volumes except the lower compartment. Hence $V_2 = 10,846 \text{ m}^3$, $V_1 = 22,894 \text{ m}^3$, $V_2/V_1 = 0.474$.

AICC Pressure											
XN2	Ratio	P (bar)	Completeness		P ₁		$\Delta V/V_2$		P ₃		
.10	4.1	6.15	1.00	1.00	5.89	5.89	.529	.529	4.31	4.31	
.08	3.6	5.40	1.00	1.00	5.21	5.21	.493	.493	3.88	3.88	
.07	3.4	5.10	.852	.958	4.42	4.78	.441	.466	3.39	3.81	
.06	3.2	4.80	.547	.672	3.22	3.61	.330	.372	2.63	2.88	
.05	2.9	4.35	.242	.386	2.27	2.55	.189	.238	2.01	2.20	

Where P_3 is the absolute pressure in bar. The first entry is completeness, P_1 , $\Delta V/V_2$, and P_3 is the "quiescent" case; the second entry is the turbulent case.

40% STEAM

The temperature in the upper compartment will be elevated. The pressure will be higher than for the no steam case. A 40% mole fraction of steam corresponds to a containment pressure of about 1.7 bar. Assume the initial pressure is 1.7 bar. The steam partial pressure will be 0.68 bar, corresponding to a saturation temperature of 362 K. Using the AICC pressure figure to be used with saturated steam, we get,

X_{H_2}	AICC		Completeness	P_1 (bar)		$\Delta V/V_2$		P_3 (bar)	
	P (bar)								
.08	7.2	.372	.400	3.64	3.79	.329	.344	2.87	3.07
.10	8.1	.666	.676	5.75	5.81	.465	.488	4.30	4.34
.12	9.0	.764	.768	7.00	7.03	.543	.544	5.08	5.10
.14	10.0	.960	.952	9.27	9.21	.615	.614	6.48	6.44

5.3 Containment Loads Issue 3, BWR Reactor Building Failure Due to Hydrogen Burns

Summary of Issue 3: Expert Panel's Assessment of Peach Bottom Reactor Building Failure Due to Hydrogen Burns

Experts consulted: Marty Plys, Fauske and Associates; Fred Torri, Pickard, Lowe & Garrick, Inc.; Pat Worthington, Nuclear Regulatory Commission.

Issue Description

What distributions characterize the uncertainty in loads, both quasi-static and impulsive, produced by hydrogen burns or detonations in the Peach Bottom reactor building?

This issue relates to the possibility that hydrogen burns within the reactor building lead to gross structural failure. In the February 1987 draft of NUREG-1150 it was determined that the efficiency of fission product retention by the reactor building was an important determinant to risk. Structural failure would reduce that efficiency. This issue focuses on hydrogen combustion loads large enough to precipitate structural failure. The expert panel was at liberty to drop cases (or subcases) of this issue for which they were certain that the induced loads from hydrogen combustion could not compromise the reactor building's integrity.

Three cases were considered for this issue:

1. Containment failure either at or following vessel breach in a long-term sequence. The suppression pool is saturated and thus large quantities of steam continue to flow into the reactor building following a leak or rupture of the containment.
2. Late containment failure at least an hour after vessel breach in a short-term sequence. The suppression pool is subcooled and thus little steam flows into the reactor building following containment failure.
3. Containment failure occurs before core damage. The suppression pool is saturated at the time of failure and large quantities of steam flow into the reactor building before core damage ensues. Steam continues to flow into the building throughout the scenario.

Cases 1 and 2 are most likely the station blackout scenarios. Case 2 may involve a loss of both ac and dc power. During the presentation of the issue, the NUREG-1150 analysts felt that ignition sources would always be present. Some members of the expert panel voiced support for this assessment. Case 3 corresponds to scenarios involving failures of the reactor protection system (i.e., there is no reactor scram). Such sequences are commonly referred to as anticipated transient without scram (ATWS).

Summary of Experts' Rationale

Expert A felt that impulse loading was not germane to this issue since ignition was certain before detonable concentrations were attained. Thus, only peak static pressure was assessed.

Three factors were considered by Expert A: (1) whether hydrogen burning would be characterized by continuous combustion (i.e., diffusion flames) or by discrete burns (i.e., multiple deflagrations); (2) given that hydrogen combustion involved deflagrations, the molar concentration at which ignition occurs; and (3) the flame speed during deflagration burns.

For those scenarios characterized by diffusion flame burning or by discrete burns with flame speeds less than 4 m/s, Expert A felt that the failure of the refueling bay blow-out panels, lifting of hatch covers, and the blow-out of interior doors would mitigate the pressure rise within the building. Expert A felt that during these scenarios, the pressure rise would not be sufficient to cause gross failure of the reactor building.

For those scenarios characterized by discrete burns with flame speeds greater than 4 m/s, Expert A assessed the distribution of the static pressure rise; the peak static pressure rises were based on calculations performed with the MELCOR and HECTR codes.

Uncertainties associated with hydrogen ignition were seen to be the largest contributor to uncertainties in peak static pressure. If the combustible gases were ignited as they escaped the containment, Expert A felt that an essentially static diffusion flame would be present. Ignition at points in the building distant from the source could occur at various concentrations of combustible gas depending on the location, available ignition sources, and the quantity of steam that had accumulated. Peak static pressure would be a strong function of the combustible gas concentration at ignition.

Expert B's approach was to assess the uncertainties associated with the type of burn, the ignition, the hydrogen (H_2) concentration in the reactor building, and the pressure rise from a hydrogen burn using a probability equation.

The Expert thought that hydrogen would either burn as a jet as it is injected into the reactor building or as a deflagration. For the blackout case, the Expert felt that a jet would not exist due to the lack of ignition sources. For the non-blackout case, the probability of a jet burn was related to the containment hydrogen concentration and temperature.

Expert B felt that the ignition probability depended on the type of burn that occurred and the on the hydrogen concentration in the reactor building. If the hydrogen burned as a jet, the Expert assumed a uniform probability distribution between reactor building hydrogen concentrations of 4 and 8%.

The Expert developed a simple model to estimate the pressure rise from a hydrogen burn using an ideal venting equation. (It was the Expert's judgment that venting controls the pressure rise.) The Expert then used

this model to calculate the pressure rise assuming various hydrogen concentrations, flame speeds, compartment volumes, and loss coefficients. From this information the Expert developed probability distribution functions for the pressure rise for reactor building hydrogen concentrations of 4, 8, and 12%.

The Expert indicated that the location of the leak was not important because the steam concentration would not differ significantly at different leak locations. Furthermore, he thought that even for high steam concentrations, large amounts of steam would condense in the reactor building and, thus, the amount of steam did not have to be explicitly considered. For the conditions presented in this issue, the Expert felt the differences between the impulsive load and the static pressure rise was negligible.

Expert C performed a base case analysis based on the calculations in the general literature and then assessed the impact by considering the differences in the assigned cases. Transitions to detonation were considered the dominant source of detonations; direct detonations were not thought possible since no ignition sources in the reactor building are likely to be strong enough. The Expert thought that ignition probability was essentially 1.0 and would occur as soon as steam de-inerting would allow. For low steam cases, the impact of flame speed on peak pressure was considered more important than in the high steam cases.

Method of Aggregation

The information from the experts was modified to average the results. For the final aggregation of this issue, two sets of cases were defined. The first set (Table 3-1) was based on the case structure, as defined in the Issue Description, and the additional resolution implied by the experts' decomposition (see Table 3-3 and Figures 3-1 to 3-6 under Aggregated Results).

Table 3-1
Final Case Set 1

<u>Final Case</u>	<u>Original Case</u>	<u>Expert Case</u>		
		<u>A</u>	<u>B</u>	<u>C</u>
1	1	1	1	1
2	1	2	1	1
3	2	1	1	2
4	2	2	1	2
5	3	3	2	3
6	3	4	2	3

The Peach Bottom plant analyst restructured the cases upon phenomenological considerations.

The second set of cases (Table 3-2) was more compatible with the accident progression event tree logic, and the results of this were used in the accident progression event tree for Peach Bottom (see Table 3-4 and Figures 3-7 through 3-12 under Aggregated Results).

Table 3-2
Final Case Set 2

<u>Final Case</u>	<u>Containment Pressure</u>	<u>Phenomenology</u>		<u>Original Case</u>	<u>Expert Case</u>		
		<u>High Steam*</u>	<u>Station Blackout</u>		<u>A**</u>	<u>B</u>	<u>C</u>
1	High	Y	Y	1	2	1	1
2	High	N	Y	2	2	1	2
3	Low	Y/N	Y	3	2	1	3
4	High	Y	N	1	2	2	1
5	High	N	N	2	2	2	2
6	Low	Y/N	N	3	2	2	3

*Corresponds to saturated suppression pool or subcooled suppression pool.

**Expert A's final results were essentially the same for all cases evaluated and his Case 2 was used for the aggregation.

The following modifications have been made to the individual expert's results in order to aggregate them.

For Expert A:

Expert A decided that the oxidized Cases 1, 2, and 3 were the same within uncertainty bounds; therefore, he did not consider them separately. Based upon what he considered as the three important sequence factors, we defined four new cases, shown in the second part of the table below. Detonation impulses will not be large enough to affect reactor building failure probability and are ignored. The probability of a burn, if DC power is available is 1.0 (see column P2 in the first part of the table below). This is based on the subsequent discussions with the Expert.

Branch Point Probabilities
(See Table A-1 in Expert A
elicitation write-up.)

<u>Factors</u>	<u>P1</u>	<u>P2</u>	<u>P3</u>	<u>P4</u>
DWMTH	.8	.5	.8	.8
OP	.2	-	-	-
DC Available		1.0		

Scenario Probabilities (See Figure A-1 in Expert A elicitation write-up.)					
<u>Cases</u>	<u>S1</u>	<u>S2</u>	<u>S3</u>	<u>S4</u>	<u>S5</u>
DWMTH,SB	.8	.08	.02	.08	.02
DWMTH,NSB	.8	.16	.04	.0	.0
OP,SB	.2	.32	.08	.32	.08
OP,NSB	.2	.64	.16	.0	.0

DWMTH - Containment failure by drywell meltthrough,
 Op - Containment failure by overpressure in the wetwell,
 SB, NSB - Station blackout (no ac or dc), any ac or dc power available.

In order to calculate the scenario probabilities for each of the four cases defined by Expert A, we put in the branch point probabilities as appropriate and multiplied.

Peak Reactor Building Pressure Distributions for Each Scenario		
<u>dp</u> <u>(kPa)</u>	<u>(S3, S5)</u>	<u>S1,S2,S4</u>
0.0	0.0	0.0*
13.78	0.35	0.667*
20.67	0.675	1.0
27.56	0.9	1.0
84.0	0.9	1.0
87.0	0.95	1.0
99.0	1.0	1.0

*The Expert said no possibility of pressures > 3 psig but did not give a distribution; therefore, we assumed linear. Following are results obtained from combining the pressure distributions with scenario probabilities.

Expert A: Peak Reactor Building Pressure Distribution: Case 1 (Original Case 1: Drywell Meltthrough; Original Case 2: Drywell Meltthrough).

<u>dp (kPa)</u>	<u>S1</u>	<u>S2</u>	<u>S3</u>	<u>S4</u>	<u>S5</u>	<u>Average</u>
0.00	0.0	0.0	0.0	0.0	0.0	0.00
13.78	0.533	0.0533	0.007	0.0533	0.007	0.654
20.67	0.8	0.08	0.0135	0.08	0.0135	0.987
27.56	0.8	0.08	0.018	0.08	0.018	0.996
84.00	0.8	0.08	0.018	0.08	0.018	0.996
87.00	0.8	0.08	0.019	0.08	0.019	0.998
99.00	0.8	0.08	0.02	0.08	0.02	1.00

Expert A: Peak Reactor Building Pressure Distribution: Case 2 (Original Case 1: Overpressure; Original Case 2: Overpressure).

<u>dp(kPa)</u>	<u>S1</u>	<u>S2</u>	<u>S3</u>	<u>S4</u>	<u>S5</u>	<u>Average</u>
0.00	0.0	0.0	0.0	0.0	0.0	0.00
13.78	0.133	0.213	0.028	0.213	0.028	0.616
20.67	0.2	0.32	0.054	0.32	0.054	0.948
27.56	0.2	0.32	0.072	0.32	0.072	0.984
84.00	0.2	0.32	0.072	0.32	0.072	0.984
87.00	0.2	0.32	0.076	0.32	0.076	0.992
99.00	0.2	0.32	0.08	0.32	0.08	1.00

Expert A: Peak Reactor Building Pressure Distribution: Case 3 (Original Case 3: Drywell Meltthrough)

<u>dp(kPa)</u>	<u>S1</u>	<u>S2</u>	<u>S3</u>	<u>S4</u>	<u>S5</u>	<u>Average</u>
0.00	0.0	0.0	0.0	0.0	0.0	0.00
13.78	0.533	0.107	0.014	0.0	0.0	0.654
20.67	0.8	0.16	0.027	0.0	0.0	0.987
27.56	0.8	0.16	0.036	0.0	0.0	0.996
84.00	0.8	0.16	0.036	0.0	0.0	0.996
87.00	0.8	0.16	0.038	0.0	0.0	0.998
99.00	0.8	0.16	0.04	0.0	0.0	1.00

Expert A: Peak Reactor Building Pressure Distribution: Case 4 (Original Case 3: Overpressure)

<u>dp(kPa)</u>	<u>S1</u>	<u>S2</u>	<u>S3</u>	<u>S4</u>	<u>S5</u>	<u>Average</u>
0.00	0.0	0.0	0.0	0.0	0.0	0.00
13.78	0.133	0.427	0.056	0.0	0.0	0.616
20.67	0.2	0.64	0.108	0.0	0.0	0.948
27.56	0.2	0.64	0.144	0.0	0.0	0.984
84.00	0.2	0.64	0.144	0.0	0.0	0.984
87.00	0.2	0.64	0.152	0.0	0.0	0.992
99.00	0.2	0.64	0.16	0.0	0.0	1.00

One can see that the final distribution is essentially the same for all cases. We will therefore use Case 2 for all cases for this expert in the aggregation. This gives slightly conservative results as more of the distribution is at higher pressure.

For Expert B:

The Expert provided an equation to calculate the probability of obtaining a specified change in pressure (dp) given the initial primary containment temperature, the initial primary containment H₂ concentration, and whether or not a blackout had occurred. We calculated the probability of obtaining a specified dp for blackout and nonblackout, for temperatures from 300 K to 1200 K, and for initial primary containment H₂ concentrations from .05 to .20. However, for the accident sequences of interest, the expected H₂

concentrations in the primary containment are expected to be high (in the range of >.15). For these cases, the detail in the lower concentration range are not important and the temperature and the H₂ concentration in primary containment are unimportant. The only variable that makes a difference is whether or not a blackout has occurred. The results are shown below.

<u>Peak Reactor Building Pressure</u>		
<u>Cumulative Probability</u>		
<u>Expert B: Case 1</u>		<u>Expert B: Case 2</u>
<u>dp</u>	<u>Blackout</u>	<u>Nonblackout</u>
	<u>Orig. Cases 1 and 2</u>	<u>Orig. Case 3</u>
0.00	0.50	0.50
1.03	0.50	0.51
1.99	0.50	0.52
3.02	0.50	0.54
4.05	0.50	0.56
5.08	0.50	0.59
6.05	0.51	0.62
7.08	0.51	0.65
8.11	0.52	0.67
9.07	0.53	0.69
10.10	0.53	0.70
15.12	0.62	0.83
20.20	0.69	0.92
25.28	0.76	0.97
30.30	0.82	1.00
50.50	0.89	1.00
101.0	0.96	1.00
151.5	1.00	1.00
202.0	1.00	1.00

Since reactor building failure is assessed at 3 psig (20 kPa), the probability of failure is .31 for the blackout case and .08 for the non-blackout case. This makes sense in terms of the Expert's elicitation since the delay in ignition in the blackout case results in higher H₂ concentrations. The Expert said that, for the conditions in this issue, the difference between the impulsive loads and the static pressure were negligible and they could be treated the same. The probability of a burn is .50 from the probability of 0 psig on the original data (see individual write-up). we subtracted the .50 and renormalized to get the conditional probability given a burn [i.e., $(x - .5) * 2$, where x = probability at $dp = y$].

For Expert C:

The probability of a burn is 1.0.

	<u>Case 1</u>	<u>Case 2</u>	<u>Case 3</u>
	PB	PB	PB
Diffusion Flame	.05	.10	.05
Deflagration	.9025	.81	.9025
Detonation	.0475	.09	.0475
Total	1.0	1.0	1.0

For detonations, the following information is applicable:

Table A peak pressure after detonation:

Pressure (kPa)	150	175	200	225	250	275	300
Probability	0.0	.10	.40	.68	.85	.94	1.0

Table B reflection fraction of original wave:

Reflection Frac	1	1.5	2.0	2.25	2.5	3.0
Probability	0.0	.10	.30	.50	.80	1.0

Table C maximum impulse of unreflected wave:

Max Impulse(kPa/s)	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
Probability	0.0	.05	.13	.25	.50	.75	.88	.95	1.0

For deflagrations, the peak reactor building pressure (dp) is:

Case 1: Station Blackout, Drywell Meltthrough or Overpressure

<u>dp (kPa)</u>	<u>Cumulative Probability</u>
1.34	0.00E-0
2.68	5.31E-4
5.37	1.44E-2
7.38	5.37E-2
8.72	9.99E-2
11.41	2.38E-1
14.09	4.14E-1
15.43	5.04E-1

Case 1: (continued)

<u>dp (kPa)</u>	<u>Cumulative Probability</u>
17.45	6.29E-1
20.80	7.95E-1
24.83	9.15E-1
27.51	9.57E-1
32.88	9.91E-1
39.59	9.99E-1
46.30	1.00E+0

Case 2: Station Blackout, Drywell Meltthrough or Overpressure

<u>dp (kPa)</u>	<u>Cumulative Probability</u>
0.00	0.00E-0
0.67	1.63E-4
1.34	1.91E-3
2.01	7.12E-3
2.68	1.68E-2
3.36	3.12E-2
4.70	7.22E-2
6.71	1.51E-1
8.72	2.36E-1
10.07	2.96E-1
12.75	4.39E-1
14.09	5.18E-1
16.10	6.26E-1
20.13	7.65E-1
22.14	8.04E-1
24.83	8.52E-1
27.51	9.03E-1
28.85	9.27E-1
30.20	9.48E-1
32.88	9.78E-1
34.89	9.90E-1
38.25	9.98E-1
42.28	1.00E-1
46.30	1.00E-0

Case 3: No Station Blackout, Drywell Melthrough or Overpressure

<u>dp (kPa)</u>	<u>Cumulative Probability</u>
3.36	0.00E-0
5.37	8.72E-4
8.05	1.01E-2
10.74	4.65E-2
12.75	1.03E-1
15.43	2.22E-1
18.79	4.18E-1
20.13	5.01E-1
22.14	6.19E-1
26.17	8.07E-1
29.53	9.05E-1
32.21	9.51E-1
38.25	9.92E-1
44.29	9.99E-1
51.00	1.00E+0

If we combine the detonation (DET) and deflagration (DEF), diffusion flame (DF) dp curves (maintaining the peak reactor building pressure bound), we get:

Case 1: Station Blackout, Drywell Melthrough or Overpressure

	<u>DEF, DF</u>	<u>DET</u>	<u>Average</u>
<u>dp (kPa)</u>	<u>Cumulative Probability</u>	<u>Cumulative Probability</u>	<u>Cumulative Probability</u>
1.34	0.00E-0	0.00E-0	0.00E-0
2.68	5.31E-4	0.00E-0	5.07E-4
5.37	1.44E-2	0.00E-0	1.38E-2
7.38	5.37E-2	0.00E-0	5.13E-2
8.72	9.99E-2	0.00E-0	9.54E-2
11.41	2.38E-1	0.00E-0	2.27E-1
14.09	4.14E-1	0.00E-0	3.95E-1
15.43	5.04E-1	0.00E-0	4.81E-1
17.75	6.29E-1	0.00E-0	6.01E-1
20.80	7.95E-1	0.00E-0	7.59E-1
24.83	9.15E-1	0.00E-0	8.74E-1
27.51	9.57E-1	0.00E-0	9.14E-1
32.88	9.91E-1	0.00E-0	9.46E-1
39.59	9.99E-1	0.00E-0	9.54E-1
46.30	1.00E+0	0.00E-0	9.55E-1
49.00	1.00E+0	0.00E-0	9.55E-1

Case 1 (Continued)

	<u>DEF. DF</u>	<u>DET</u>	<u>Average</u>
<u>dp</u> <u>(kPa)</u>	<u>Cumulative</u> <u>Probability</u>	<u>Cumulative</u> <u>Probability</u>	<u>Cumulative</u> <u>Probability</u>
74.00	1.00E+0	1.00E-1	9.60E-1
99.00	1.00E+0	4.00E-1	9.73E-1
24.00	1.00E+0	6.80E-1	9.86E-1
149.00	1.00E+0	8.50E-1	9.93E-1
174.00	1.00E+0	9.40E-1	9.97E-1
199.00	1.00E+0	1.00E+0	1.00E-0

Case 2: Station Blackout, Drywell Melthrough or Overpressure

	<u>DEF. DF</u>	<u>DET</u>	<u>Average</u>
<u>dp</u> <u>(kPa)</u>	<u>Cumulative</u> <u>Probability</u>	<u>Cumulative</u> <u>Probability</u>	<u>Cumulative</u> <u>Probability</u>
0.00	0.00E-0	0.00E-0	0.00E-0
0.67	1.63E-4	0.00E-0	1.49E-4
1.34	1.91E-3	0.00E-0	1.75E-3
2.01	7.12E-3	0.00E-0	6.51E-3
2.68	1.68E-2	0.00E-0	1.54E-2
3.36	3.12E-2	0.00E-0	2.85E-2
4.70	7.22E-2	0.00E-0	6.61E-2
6.71	1.51E-1	0.00E-0	1.38E-1
8.72	2.36E-1	0.00E-0	2.16E-1
10.07	2.96E-1	0.00E-0	2.71E-1
12.75	4.39E-1	0.00E-0	4.02E-1
14.09	5.18E-1	0.00E-0	4.74E-1
16.10	6.26E-1	0.00E-0	5.73E-1
20.13	7.65E-1	0.00E-0	7.00E-1
22.14	8.04E-1	0.00E-0	7.36E-1
24.83	8.52E-1	0.00E-0	7.80E-1
27.51	9.03E-1	0.00E-0	8.26E-1
28.85	9.27E-1	0.00E-0	8.48E-1
30.20	9.48E-1	0.00E-0	8.67E-1
32.88	9.78E-1	0.00E-0	8.95E-1
34.89	9.90E-1	0.00E-0	9.06E-1
38.25	9.98E-1	0.00E-0	9.13E-1
42.28	1.00E-0	0.00E-0	9.15E-1
46.30	1.00E-0	0.00E-0	9.15E-1
49.00	1.00E-0	0.00E-0	9.15E-1
74.00	1.00E+0	1.00E-1	9.24E-1

Case 2 (Continued)

	<u>DEF. DF</u>	<u>DET</u>	<u>Average</u>
<u>dp</u> <u>(kPa)</u>	<u>Cumulative</u> <u>Probability</u>	<u>Cumulative</u> <u>Probability</u>	<u>Cumulative</u> <u>Probability</u>
99.00	1.00E+0	4.00E-1	9.49E-1
124.00	1.00E+0	6.80E-1	9.73E-1
149.00	1.00E+0	8.50E-1	9.87E-1
174.00	1.00E+0	9.40E-1	9.95E-1
199.00	1.00E+0	1.00E+0	1.00E-0

Case 3 No Station Blackout, Drywell Melthrough or Overpressure

	<u>DEF. DF</u>	<u>DET</u>	<u>Average</u>
<u>dp</u> <u>(kPa)</u>	<u>Cumulative</u> <u>Probability</u>	<u>Cumulative</u> <u>Probability</u>	<u>Cumulative</u> <u>Probability</u>
3.36	0.00E-0	0.00E-0	0.00E-0
5.37	8.72E-4	0.00E-0	8.33E-4
8.05	1.01E-2	0.00E-0	9.65E-3
10.74	4.65E-2	0.00E-0	4.44E-2
12.75	1.03E-1	0.00E-0	9.84E-2
15.43	2.22E-1	0.00E-0	2.12E-1
18.79	4.18E-1	0.00E-0	3.99E-1
20.13	5.01E-1	0.00E-0	4.78E-1
22.14	6.19E-1	0.00E-0	5.91E-1
26.17	8.07E-1	0.00E-0	7.71E-1
29.53	9.05E-1	0.00E-0	8.64E-1
32.21	9.51E-1	0.00E-0	9.08E-1
38.25	9.92E-1	0.00E-0	9.47E-1
44.29	9.99E-1	0.00E-0	9.54E-1
51.00	1.00E+0	0.00E-1	9.55E-1
74.00	1.00E+0	1.00E-1	9.60E-1
99.00	1.00E+0	4.00E-1	9.73E-1
124.00	1.00E+0	6.80E-1	9.86E-1
149.00	1.00E+0	8.50E-1	9.93E-1
174.00	1.00E+0	9.40E-1	9.97E-1
199.00	1.00E+0	1.00E+0	1.00E-0

Since the failure pressure of the reactor building is 40 kPa, any detonation will result in failure.

Aggregated Results

The results are presented on the following pages.

Table 3-3
Average of Experts' Elicitations. Final Cases Set 1
Peak Reactor Building Pressure in kPa

FC1-1: Case 1: Drywell Meltthrough (DMM)															
Fractile	0.001	0.010	0.050	0.100	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900	0.950	0.990	0.999
Expert A	0.021	0.211	1.054	2.107	4.214	6.321	8.428	10.535	12.642	14.732	16.801	18.870	19.904	22.967	93.000
Expert B	5.128	5.565	8.590	11.216	14.004	17.297	20.926	24.554	28.627	38.957	57.714	93.786	119.937	145.187	150.869
Expert C	2.780	4.601	7.310	8.814	10.858	12.575	14.168	15.750	17.433	19.549	22.237	26.572	36.235	138.286	190.667
AVERAGE	0.063	0.632	3.106	5.662	9.045	11.578	13.633	15.701	17.865	20.403	25.436	46.033	88.171	138.786	174.000
FC1-2: Case 1: Overpressure (OP)															
Expert A	0.022	0.224	1.119	2.237	4.474	6.711	8.948	11.185	13.422	15.523	17.599	19.674	21.053	86.250	97.500
Expert B	5.128	5.565	8.590	11.216	14.004	17.297	20.926	24.554	28.627	38.957	57.714	93.786	119.937	145.187	150.869
Expert C	2.780	4.601	7.310	8.814	10.858	12.575	14.168	15.750	17.433	19.549	22.237	26.572	36.235	138.286	190.667
AVERAGE	0.067	0.671	3.278	5.848	9.305	11.801	13.892	15.985	18.279	20.747	25.897	47.758	88.539	138.786	174.000
FC1-3: Case 2: DMM															
Expert A	0.021	0.211	1.054	2.107	4.214	6.321	8.428	10.535	12.642	14.732	16.801	18.870	19.904	22.967	93.000
Expert B	5.128	5.565	8.590	11.216	14.004	17.297	20.926	24.554	28.627	38.957	57.714	93.786	119.937	145.187	150.869
Expert C	1.026	2.273	4.126	5.648	8.308	10.663	12.709	14.618	16.957	20.130	25.995	33.794	100.042	158.375	194.000
AVERAGE	0.063	0.629	2.791	4.830	7.847	10.767	13.026	15.232	17.805	20.892	27.626	53.201	95.584	142.919	184.000
FC1-4: Case 2: OP															
Expert A	0.022	0.224	1.119	2.237	4.474	6.711	8.948	11.185	13.422	15.523	17.599	19.674	21.053	86.250	97.500
Expert B	5.128	5.565	8.590	11.216	14.004	17.297	20.926	24.554	28.627	38.957	57.714	93.786	119.937	145.187	150.869
Expert C	1.026	2.273	4.126	5.648	8.308	10.663	12.709	14.618	16.957	20.130	25.995	33.794	100.042	158.375	194.000
AVERAGE	0.067	0.668	2.911	4.896	8.159	10.986	13.284	15.538	18.285	21.644	27.924	57.032	95.069	142.919	184.000
FC1-5: Case 3: DMM															
Expert A	0.021	0.211	1.054	2.107	4.214	6.321	8.428	10.535	12.642	14.732	16.801	18.870	19.904	22.967	93.000
Expert B	0.052	0.515	2.247	3.535	5.403	7.080	10.100	12.031	13.962	16.249	19.071	23.248	26.117	29.463	30.216
Expert C	5.421	8.077	10.948	12.788	15.147	17.011	18.807	20.521	22.341	24.580	27.218	31.723	40.839	138.286	190.667
AVERAGE	0.045	0.449	2.170	3.906	6.690	9.806	12.427	14.575	16.745	18.894	21.367	25.897	29.510	94.631	174.000
FC1-6: Case 3: OP															
Expert A	0.022	0.224	1.119	2.237	4.474	6.711	8.948	11.185	13.422	15.523	17.599	19.674	21.053	86.250	97.500
Expert B	0.052	0.515	2.247	3.535	5.403	7.080	10.100	12.031	13.962	16.249	19.071	23.248	26.117	29.463	30.216
Expert C	5.421	8.077	10.948	12.788	15.147	17.011	18.807	20.521	22.341	24.580	27.218	31.723	40.839	138.286	190.667
AVERAGE	0.047	0.468	2.242	4.034	6.864	10.213	12.703	14.843	17.020	19.165	21.833	26.206	29.925	96.472	174.000

Figure 3.1 (left). Peak Reactor Building Pressure (kPa). Case 1 Drywell Meltthrough (DWM).
 Figure 3-2 (right). Peak Reactor Building Pressure (kPa). Case 1 Drywell Meltthrough (OP).

Final Case Set 1 - 3
CASE 2 DWM

Final Case Set 1 - 4
CASE 2 OP

Figure 3-3 (left). Peak Reactor Building Pressure (kPa) Case 2 DWM.
Figure 3-4 (right). Peak Reactor Building Pressure (kPa) Case 2 OP.

Final Case Set 1 - 5
CASE 3 DWM

Final Case Set 1 - 6
CASE 3 OP

Figure 3-5 (left). Peak Reactor Building Pressure (kPa) Case 3 DWM.
Figure 3-6 (right). Peak Reactor Building Pressure (kPa) Case 3 OP.

Table 3-4
Peak Reactor Building Pressure (kPa) Final Cases Set 2

FC2-1 Case 1, Station Blackout, High Pressure, High Steam															
Fractile	0.001	0.010	0.050	0.100	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900	0.950	0.990	0.999
Expert A	0.021	0.211	1.034	2.107	4.214	6.321	8.428	10.535	12.642	14.732	16.801	18.870	19.904	22.967	93.000
Expert B	5.128	5.565	8.590	11.216	14.004	17.287	20.926	24.554	28.627	38.957	57.714	93.788	119.937	145.187	150.869
Expert C	2.780	4.601	7.310	8.814	10.858	12.575	14.168	15.750	17.433	19.549	22.237	26.572	36.235	138.286	190.667
AVERAGE	0.063	0.632	3.106	5.662	8.045	11.578	13.633	15.701	17.865	20.403	25.436	46.033	88.171	138.786	174.000
FC2-2 Case 2, Station Blackout, High Pressure, Low Steam															
Expert A	0.022	0.224	1.119	2.237	4.474	6.711	8.948	11.185	13.422	15.523	17.599	19.674	21.053	86.250	97.500
Expert B	5.128	5.565	8.590	11.216	14.004	17.287	20.926	24.554	28.627	38.957	57.714	93.788	119.937	145.187	150.869
Expert C	1.026	2.273	4.126	5.648	8.308	10.663	12.709	14.618	16.957	20.130	25.995	33.794	100.042	158.375	194.000
AVERAGE	0.067	0.668	2.811	4.996	8.159	10.898	13.294	15.558	18.265	21.644	27.824	57.032	95.969	142.919	184.000
FC2-3 Case 3, Station Blackout, Low Pressure, High or Low Steam															
Expert A	0.021	0.211	1.034	2.107	4.214	6.321	8.428	10.535	12.642	14.732	16.801	18.870	19.904	22.967	93.000
Expert B	5.128	5.565	8.590	11.216	14.004	17.287	20.926	24.554	28.627	38.957	57.714	93.788	119.937	145.187	150.869
Expert C	5.421	8.077	10.948	12.786	15.147	17.011	18.807	20.521	22.341	24.580	27.218	31.723	40.839	138.286	190.667
AVERAGE	0.063	0.632	3.161	5.907	10.335	13.080	15.473	17.754	20.004	23.318	27.848	46.132	88.171	138.786	174.000
FC2-4 Case 4, No Station Blackout, High Pressure, High Steam															
Expert A	0.022	0.224	1.119	2.237	4.474	6.711	8.948	11.185	13.422	15.523	17.599	19.674	21.053	86.250	97.500
Expert B	0.052	0.515	2.248	3.535	5.403	7.080	10.100	12.031	13.962	16.249	19.071	23.248	26.117	29.463	30.216
Expert C	2.780	4.601	7.310	8.814	10.858	12.575	14.168	15.750	17.433	19.549	22.237	26.572	36.235	138.286	190.667
AVERAGE	0.047	0.468	2.238	3.956	6.569	9.088	11.376	13.264	15.110	17.185	18.466	23.429	27.062	96.472	174.000
FC2-5 Case 5 No Station Blackout, High Pressure, Low Steam															
Expert A	0.021	0.211	1.034	2.107	4.214	6.321	8.428	10.535	12.642	14.732	16.801	18.870	19.904	22.967	93.000
Expert B	0.052	0.515	2.248	3.535	5.403	7.080	10.100	12.031	13.962	16.249	19.071	23.248	26.117	29.463	30.216
Expert C	1.026	2.273	4.126	5.648	8.308	10.663	12.709	14.618	16.957	20.130	25.995	33.794	100.042	158.375	194.000
AVERAGE	0.045	0.447	2.084	3.525	5.764	7.972	10.425	12.450	14.427	16.674	19.276	24.734	29.746	120.875	164.000
FC2-6 Case 6 No Station No Station Blackout, Low Pressure, High or Low Steam															
Expert A	0.022	0.224	1.119	2.237	4.474	6.711	8.948	11.185	13.422	15.523	17.599	19.674	21.053	86.250	97.500
Expert B	0.052	0.515	2.247	3.535	5.403	7.080	10.100	12.031	13.962	16.249	19.071	23.248	26.117	29.463	30.216
Expert C	5.421	8.077	10.948	12.786	15.147	17.011	18.807	20.521	22.341	24.580	27.218	31.723	40.839	138.286	190.667
AVERAGE	0.047	0.468	2.242	4.034	6.864	10.213	12.705	14.843	17.020	19.166	21.633	26.206	29.925	96.472	174.000

Final Case Set 2 - 1
SB, Hi Press, Hi STM

Final Case Set 2 - 2
SB, Hi Press, Low STM

Figure 3-7 (left). Peak Reactor Building Pressure (kPa) Case 1: SB, High Pressure, High Steam.
Figure 3-8 (right). Peak Reactor Building Pressure (kPa) Case 2: SB, High Pressure, Low Steam.

Final Case Set 1 - 3
SB, Low Press. Hi or Low STM

Final Case Set 2 - 4
nSB, Hi Press. Hi STM

Figure 3-9 (left). Peak Reactor Building Pressure Case 3: SB, Low Pressure, High or Low Steam.
Figure 3-10 (right). Peak Reactor Building Pressure Case 4: No SB, High Pressure, High Steam.

Final Case Set 2 - 5
nSB, Hi Press. Low STM

Final Case Set 2 - 6
nSB, Low Press. Hi or Low STM

Figure 3-11 (left). Peak Reactor Building Pressure Case 5: No SB, High Pressure, Low Steam.
 Figure 3-12 (right). Peak Reactor Building Pressure Case 6: No SB, Low Pressure, High or Low Steam.

Individual Elicitations for Issue 3

Expert A's Elicitation

Issue 3: Peach Bottom Reactor Building Failure Due to Hydrogen Burns

Description of Expert A's Rationale/Methodology

Expert A felt that impulse loading was not germane to this issue since ignition was certain before detonable concentrations were attained. Thus, only peak static pressure was assessed. Figure A-1 below shows the decomposition that Expert A used to address this issue.

Figure A-1. Expert A's Decomposition Tree

Three factors were considered:

1. Whether hydrogen burning would be characterized by continuous combustion (i.e. diffusion flames) or by discrete burns (i.e., multiple deflagrations).
2. Given that hydrogen combustion involved deflagrations, the molar concentration at which ignition occurs becomes important. Expert A divided the ignition threshold into two regions: ignition at molar concentrations below 8% and ignition at molar concentrations above 8%.
3. Flame speed during deflagration burns is also a key determinant of the peak static pressure. As with hydrogen concentration at ignition, Expert A divided the possible range of flame speeds into two regions: flame speeds less than 4 m/s and flame speeds at or above 4 m/s.

The tree shown in Figure A-1 results in five scenarios (numbered 1 through 5 in Figure A-1). A subjective probability was assigned to each branch point in the tree (P_1 to P_4). These probabilities are multiplied to arrive at an estimate of the probability for each scenario.

For scenarios 1, 2, and 4 Expert A felt that the failure of the refueling bay blow-out panels, lifting of hatch covers, and the blow-out of interior doors would mitigate the pressure rise within the building. Based on a preliminary review of the elicitations from the structural review panel by the analysts and Expert A's own knowledge, it was judged that gross failure of the reactor building would require static pressures greater than 20 kPa over atmospheric (3 psig). Expert A was certain that scenarios 1, 2, and 4 could not raise the reactor building pressure more than 20 kPa. Further assessment of these scenarios was thus not required.

For scenarios 3 and 5 Expert A considered the distribution of the static pressure rise for each of the three cases and the probability for the branch probability defining scenarios. Peak static pressure was assessed for scenario 5 given Case 2 based on calculations performed with the MELCOR and HECTR codes. These calculations were performed by SNL and Oak Ridge National Laboratory (ORNL). The ORNL calculations were for the Brown's Ferry plant which has a considerably different design from Peach Bottom. Expert A assigned a subjective probability that the result obtained in each calculation considered was correct for the case being assessed. A much lower probability was assigned to the ORNL calculations being correct since they were for a different plant. However, Expert A felt that there was some chance that the Brown's Ferry model results would reflect what would happen at Peach Bottom. Thus the combined SNL results were assigned a 0.9 weight. A weight of 0.1 was assigned to the ORNL results.

The Expert determined, as a result of the assessment of Case 2, that separate assessments for Cases 1 and 3 of this issue were not needed except as indicated by the availability of ac or dc power. Expert A stated that the uncertainties in the assessment were large relative to the differences between the cases. Case 2 was selected for assessment since he felt that the available code runs corresponded most closely to these cases.

Results of Expert A's Elicitation

Expert A assessed Case 2 of this issue assuming that the scenario was a short-term station blackout with failure of both ac and dc power (corresponding to the TBUX plant damage state). Containment failure was assumed to occur as a result of drywell meltthrough. The various probabilities shown in Figure A-1 were assessed as indicated in Table A-1.

Table A-1
Decomposition Tree Probabilities
(Case 2, Station Blackout With Drywell Meltthrough)

Probability (See Figure A-1)	Meaning	Assessed Value
1	Probability that diffusion flame occurs	0.8
2	Probability that combustion begins below 8% molar H ₂ concentration	0.5
3	Probability that deflagration flame speed is below 4 m/s given ignition at or below 8% H ₂ concentration	0.8
4	Probability that deflagration flame speed is below 4 m/s given ignition above 8% H ₂ concentration	0.8

If the containment failure mode was overpressurization of the wetwell, Expert A would assign probability 1 a value of 0.2 rather than 0.8. If dc power were available, probability 2 would increase but Expert A did not provide a value.

Table A-2 shows the various calculations that Expert A considered and the weights assigned to each. Figure A-2 shows the resulting cumulative distribution function for peak static pressure. The distribution shown is bimodal. Expert A stated that this feature correctly represented his opinion and that peak static pressures in the range from 130 to 180 kPa would essentially never occur since one of the two models used was, in fact, correct. These results correspond to Sequence 5. No assessment was provided for Sequence 3.

Expert A felt that adjustment should be made to his result based on the quantity of hydrogen produced in-vessel (assessed by the In-vessel Phenomena Expert Panel) and the size and location of containment failure (assessed by the Structural Expert Panel). For in-vessel hydrogen production, Expert A recommended linear extrapolation of his results based on the amount of hydrogen produced in-vessel. He stated that his results corresponded to 910 kg of hydrogen being produced. To adjust for containment leak area, Expert A recommended using the variation in peak pressure seen with leak area in the ORNL calculations as a basis for extrapolating his results.

Table A-2
Assessment of Peak Reactor Building Pressure

Characteristics of Computer Calculation			Expert A's Assessment of Applicability		
Assumed Ignition* Threshold (% H ₂ by Volume)	Assumed Flame* Speed (m/s)	Cal. Peak* Pressure (kPa)	Rel. Wgt. For Group (W _G)	Rel. Wgt. Within Group (W _S)	Subjective Probability (W _G x W _S)
10	4	114	0.45	0.30	0.135
10	8	125		0.30	0.135
12	4	116		0.20	0.09
12	8	129		0.20	0.09
8	?	188	0.1	0.33	0.033
8	?	199		0.33	0.033
8	?	185		0.33	0.033
8	4	111	0.45	0.5	0.225
8	8	121		0.5	0.225

*These values were provided by Expert A.

Figure A-2. Reactor Building Pressure Rise

Sources of Uncertainty

The major sources of uncertainty for this issue that were identified by Expert A are denoted by the branch points of the decomposition tree shown in Figure A-1. Uncertainties associated with hydrogen ignition were seen to be the largest contributor to uncertainties in peak static pressure. If the combustible gases were ignited as they escaped the containment, Expert A felt that an essentially static diffusion flame would be present and that building pressurization became a moot question. On the other hand, ignition at points in the building distant from the source could occur at various concentrations of combustible gas depending on the location, available ignition sources, and the quantity of steam that had accumulated. Peak static pressure would be a strong function of the combustible gas concentration at ignition.

The rapidity of the burn was seen as the second major source of uncertainty. High flame speeds result in rapid burns which produce relatively high static pressures.

Correlations With Other Variables

No correlations were specified by the Expert for this issue as noted above (i.e., in-vessel hydrogen production and containment failure size and location).

Suggested Methods for Reducing Uncertainty

No suggestions were made for reducing uncertainties.

Expert B's Elicitation

Issue 3: Peach Bottom Reactor Building Failure Due to Hydrogen Burns

Description of Expert B's Rationale/Methodology

The Expert indicated that the location of the leak was not important because the steam concentration would not be significantly different at different leak locations. Furthermore, he thought that even for high steam concentrations, large amounts of steam would condense in the reactor building and, thus, the amount of steam did not have to be explicitly considered. Therefore, the only two cases the Expert considered were blackout sequences and non-blackout sequences. The Expert defined a blackout as the loss of both ac and dc power.

For the conditions presented in this issue, the Expert felt the differences between the impulsive load and the static pressure rise was negligible. Therefore, in his assessment, the Expert considered flame acceleration but not detonations.

The Expert's approach was to filter into his assessment the uncertainties associated with the type of burn, the probability of ignition, the hydrogen (H_2) concentration in the reactor building, and the pressure rise from a hydrogen burn. To do this, the Expert developed the following probability equation:

$$p(\Delta P|X_c, B_s) = \int_0^{X_{max}} [p_{jet}(X_c, T) \cdot p(\Delta P|X_{rb}) \cdot p(burn|X_{rb}, B_s) + p_{njet}(X_c, T) \cdot p(\Delta P|X_{rb}) \cdot p(burn|X_{rb}, B_s)] p(X_{rb}|X_c) \cdot dX_{rb} \quad (1)$$

where

- ΔP - the pressure increase from the burn;
- X_c - the concentration of hydrogen in the containment;
- B_s - the blackout state (i.e., blackout or nonblackout);
- X_{max} - the maximum H_2 concentration in the reactor building;
- p_{jet} - the probability of a jet;
- T - the containment temperature;
- X_{rb} - the H_2 concentration in the reactor building;
- burn - the ignition state;
- p_{njet} - the probability of no jet.

The term $p(X_{rb}|X_c)$ represents the uncertainty in the hydrogen concentration in the reactor building, $p(burn|X_{rb}, B_s)$ represents the probability that the hydrogen mixture will ignite and burn, $p_{jet}(X_c, T)$ is the probability the hydrogen will burn as a jet, and $p(\Delta P|X_{rb})$ represents the uncertainty in the pressure rise which results from the hydrogen burn

The Expert thought that there were two possibilities for the hydrogen burn: (1) it could either burn as a jet as it is injected into the reactor building or (2) it could burn as a deflagration. For the blackout case, he felt a jet could not exist because of the lack of ignition sources. For the non-blackout case the probability of a jet, P_{jet} , was related to the containment hydrogen concentration and temperature. The Expert based the ignition probability of a jet on data presented in Figure B-1. Above a containment temperature of 1060 K or above a containment hydrogen concentration of 12% the probability of a jet burn is 1. If the hydrogen concentration is below 12% and the containment temperature is less than 1060 K, the probability of a jet depends on both temperature and hydrogen concentration. To determine the probability of a jet in this region, the Expert provided the following set of equations:

$$X_c = 9.6 \times 10^{-5} (925 - T) + 0.06 \text{ for } 300 < T < 925 \text{ K} \quad (2)$$

and

$$X_c = 4.44 \times 10^{-4} (1060 - T) \text{ for } 925 < T < 1060 \text{ K} \quad (3)$$

Above this curve the probability of a jet is 1 and below this curve the probability of a jet is 0. In other words, if the hydrogen concentration in the containment is greater than the hydrogen concentration predicted by this equation, then the probability of a jet is 1; otherwise, the probability of a jet is zero.

The ignition probability depends on the type of burn that occurs and the hydrogen concentration in the reactor building. If the hydrogen burns as a jet, the Expert assumed a uniform probability distribution between reactor building hydrogen concentrations of 4% and 8% for the non-blackout case and zero for the blackout case. For deflagrations, the Expert chose a low "anchor" (lower bound) and a high "anchor" (upper bound) for ignition probability. The low anchor was assigned a probability of 0 and the high anchor a probability of 1. The median was arbitrarily chosen as the midpoint between the low and high anchors. For the non-blackout case the low anchor corresponded to the lower flammability limit for upward flame propagation (4%). Similarly, the high anchor corresponded to the lower flammability limit for downward flame propagation (8%). For the blackout case, the Expert indicated that there should still be sources of sparks throughout the building. For this case the low anchor corresponded to the lower flammability limit for downward propagation (8%). The Expert thought that hydrogen mixture of 12% would be highly flammable and, therefore, chose this value as his high anchor.

The next step of the Expert's methodology was to develop probability distributions for the pressure rise that results from a hydrogen burn in the reactor building. The Expert indicated that when a burn occurs in a single volume, the pressure is far below the ideal pressure because the reactor building rooms are vented through large areas. It was the opinion of the Expert that venting controls the pressure rise. The Expert used an ideal venting equation to estimate the pressure rise from a hydrogen burn. By assuming some reasonable initial conditions and properties the Expert was able to get good agreement between his simple model (see attached

Figure B-1. Ignition of a Hydrogen-Nitrogen Jet (Without Sodium) as a Function of Jet Temperature.

appendix to this elicitation). He then used his model to calculate the pressure rise assuming various hydrogen concentrations, flame speeds, compartment volumes, and loss coefficients. From this information the Expert developed probability distribution functions for the pressure rise for reactor building hydrogen concentrations of 4, 8, and 12%. At hydrogen concentrations of 4% the Expert felt the pressure rise from a burn would be low because of incomplete combustion. The low end of the distribution represents repetitive burns or incomplete burns. Midway between the 0 fractile and the median (at the 0 fractile), the value the Expert chose corresponds to the pressure rise required to open the blow-out panels. The pressure rise at the median was based on hand calculations. Similarly, the high "anchor" was based on hand calculations recognizing a low flame acceleration and incomplete combustion. At hydrogen concentrations of 8 and 12%, the low anchor values correspond to the pressure rise required to open the blowout panels. For the high anchor values the Expert assumed a highly accelerated flame. The median values are based on a moderate flame acceleration. The Expert felt that the pressure rises he provided for hydrogen concentrations at 8 and 12% may be too large because the ideal vent formula is not dynamic, and these pressures may cause other vent areas to open and thus allow greater venting.

To express the uncertainty in the hydrogen concentration in the reactor building the Expert assumed a uniform distribution between two hydrogen concentrations which are related to the range of hydrogen concentrations

considered for the ignition probability. For a jet the Expert assumed a uniform distribution between 4 and 8% hydrogen. For deflagrations, the Expert assumed a uniform distribution between the low anchor for ignition probability and X_{max} where

$$X_{max} = \min(\text{high anchor for ignition}, X_{max}^*)$$

where X_{max}^* is the maximum hydrogen concentration in the reactor building assuming there are no hydrogen burns. Although the Expert did not assess this value, he felt that it should be obtained from a deterministic calculation (e.g., MELCOR calculation). It should be noted that X_{max}^* is a function of the hydrogen concentration in the containment.

Results of Expert B's Elicitation

Jet Probability

For the blackout case, the probability that the hydrogen will burn as a jet is zero. For the non-blackout case, the following two equations are used to determine the probability of a jet:

$$X_c = 9.6 \times 10^{-5} (925 - T) + 0.06 \text{ for } 300 < T < 925 \text{ K} \quad (2)$$

and

$$X_c = 4.44 \times 10^{-4} (1060 - T) \text{ for } 925 < T < 1060 \text{ K.} \quad (3)$$

In other words, if the hydrogen concentration in the containment is greater than the hydrogen concentration predicted by these equations, then the probability of a jet is 1; otherwise, the probability of a jet is zero.

Ignition Probability

The ignition probability for a jet is a uniform distribution between reactor building hydrogen concentrations of 4% and 8%. These values are tabulated in Table B-1. For a deflagration burn, the ignition probabilities for the blackout case and non-blackout case are presented in Table B-2.

Table B-1
Ignition Probabilities for a Jet

Reactor building H ₂ Concentration (%)	Cumulative Probability	
	NBO	BO
4	0.0	0.0
8	1.0	0.0

Table B-2
Ignition Probabilities for Deflagrations

<u>Cumulative Probability</u>	<u>Rx Bldg H₂ Concentration (%)</u>	
	<u>Blackout</u>	<u>Nonblackout</u>
0.0	8.0	4.0
0.1	9.0	5.0
0.5	10.0	6.0
0.9	11.0	7.0
1.0	12.0	8.0

Pressure Rise Probability

The pressure rise probabilities for reactor building hydrogen concentrations of 4, 8, and 12% are presented in Table B-3. The Expert indicated that pressure rise versus hydrogen concentration curves for a given fractile are linear from 4 to 11% hydrogen and have a "S" shape from 11 to 12% hydrogen.

Table B-3
Pressure Rise in Reactor Building
Due to a Hydrogen Burn (Atm.)

<u>Cumulative Probability</u>	<u>Rx Bldg H₂ Concentration (%)</u>		
	<u>4%</u>	<u>8%</u>	<u>12%</u>
0.00	0.00	0.05	0.05
0.05	(0.005)	(0.075)	0.10
0.10	(0.01)	0.10	(0.20)
0.50	0.05	0.15	0.30
0.90	0.08	0.25	1.00
1.00	0.10	0.30	2.00

Reactor Building Hydrogen Concentration Probability

To express the uncertainty in the hydrogen concentration in the reactor building the Expert assumed a uniform distribution between a low and high anchor. The results are presented in Table B-4.

Table B-4
Reactor Building Hydrogen Concentration Uncertainty

<u>Cumulative Probability</u>	<u>Jet</u>	<u>Deflagration</u>	
		<u>Blackout</u>	<u>Nonblackout</u>
0.0	4.0	8.0	4.0
1.0	8.0	X_{max}	X_{max}

X_{max} = min(12%, X_{max}^*) for blackout

X_{max} = min(8%, X_{max}^*) for non-blackout

X_{max}^* = Maximum hydrogen concentration in the reactor building assuming there are no hydrogen burns.

Sources of Uncertainty

The major sources of uncertainty were the values used for flame acceleration and the "effective" vent areas

Correlations with Other Variables

No correlations were discussed between variables in the event trees and the variables discussed as part of this issue.

Suggested Methods for Reducing Uncertainty

No recommendations were made for reducing uncertainty

APPENDIX

Expert B's Model

The Expert's model equations for continuity and energy assumed ideal and calorically perfect gases:

$$(1) \quad \frac{dn}{dt} = -A \frac{2n (P - P_a)}{MVk_e}$$

$$(2) \quad \frac{dP}{dt} = \frac{\dot{Q}R}{Mc_v V} + \frac{\gamma P}{n} \left(\frac{dn}{dt} \right)$$

where

n = number of gas moles

A = vent area from the building

P = instantaneous pressure

P_a = downstream (atmospheric) pressure

M = molecular weight (assumed constant)

k_e = loss coefficient accounting for all intercompartmental junctions

$\dot{Q}$ = energy production rate from burn

R = ideal gas constant

c_v = specific heat at constant volume

γ = C_p/C_v

The maximum pressure rise is thus given by

$$(3) \quad \frac{\dot{Q}R}{Mc_v V} = \frac{\gamma AP}{n} \left[\frac{2n (P - P_a)}{MVk_e} \right]^{1/2}$$

The energy release term is given by knowledge of the hydrogen concentration, the burning enthalpy release, and the burn time, allowing further simplification:

$$(4) \quad \frac{s \Delta h}{Mc_v T_o \tau} = \frac{\gamma AP}{P_o} \left[\frac{2 (P - P_a)}{n_o MVk_e} \right]^{1/2}$$

where the subscript o denotes initial reactor building conditions, x = hydrogen concentration, Δh = burn enthalpy, τ = burn time.

The purpose of these equations is to demonstrate the efficacy of venting on reduction of the combustion pressure rise, and thus show that adiabatic, isochoric values for the pressure rise are not appropriate to reactor building analysis.

For purely illustrative purposes, the expert applied (3) to reproduce Haskin's [2] results. He assumed:

$$V = 10^4 \text{ m}^3, \Delta h = 60\text{E}6 \text{ J/kg. mol H}_2,$$

$$P_o = 10^5 \text{ Pa}, T_o = 400 \text{ K}, n_o = 301 \text{ kg. mol},$$

$$M = 20, c_v = 1000 \text{ J/kgK}$$

$$L = 10 \text{ m for } (\tau = L/U)$$

CASE INPUT

Case	B3	B4	B11	B12	B19	B20
x_{H_2}	.08	.08	.10	.10	.12	.12
u_{Burn}	4	8	4	8	4	8

DERIVE

τ (s)	2.5	1.25	2.5	1.25	2.5	1.25
n_{H_2}	24	24	30	30	36	36
ΔQ (J)	1444E6	1444E6	1800E6	1800E6	2160E6	2160E6
$\dot{Q}$ (W)	578E6	1155E6	720E6	1440E6	864E6	1728E6

Assuming $A = 22 \text{ m}^2$ blowout panel area and
 $\Delta P = \text{kPa}$ controlling the venting,

--- Pressure in Bars ---

Case	B3	B4	B11	B12	B19	B20
$P(\text{Haskin})[2]$	1.11	1.21	1.13	1.25	1.15	1.29
$k_o = 2.5$	1.07	1.17	--	1.22	1.11	1.28
$k_o = 5.0$	1.11	1.26	1.14	1.35	1.18	1.43
$k_o = 7.5$	1.14	1.34	--	--	--	--

While the agreement is very good, a noticeable bias exists such that the effective k_e appears to decrease with increased final pressure. Thus, the simple model can be used to evaluate venting from a reactor building, but some of the physics of intercompartmental flow is obscured by its use. That is, the real building in Haskin's calculations consisted of a series of rooms and hatches which one lumped into the single k_e . The "round numbers" used in the sample calculation also contribute to a bias in k_e .

The fundamental conclusion to be drawn from the analysis is that the reactor building pressure response to hydrogen burns is governed by venting. Such a pressure rise can be accurately predicted with a simple model which is "tuned" to the specific building, and the simple model can be used to analyze sensitivity and generate probability distributions.

Expert C's Elicitation

Issue 3: Peach Bottom Reactor Building Failure Due to Hydrogen Burns

Description of Expert C's Rationale/Methodology

The Expert performed a base case analysis based on the calculations in the general literature and then assessed how the differences in our cases would affect the results. The steam will result in transitions to detonation being the dominant source of detonations; direct detonations are not possible since no sources in the reactor building are likely to be strong enough. The Expert thought that ignition was essentially 1.0 and would occur as soon as steam de-inerting would allow. For low steam cases, flame speed will be more important than in the high steam cases in affecting the peak pressure. The Expert did not present the results in terms of hydrogen concentration but from the computer runs included the variation in possible hydrogen production in the results.

Results of Expert C's Elicitation

The three cases are: Case 1, high pressure, steam; Case 2, high pressure, little steam; and Case 3 low pressure, steam. (DF = diffusion flame, DET = detonation, DEF = deflagration, FS = flame speed, PP = peak pressure, RF = reflection function, UI = maximum unreflected impulse (mode, N), B_β = beta distribution.

Case 1:

DF = .05 (.10)

DEF = .95 (.90)

Delayed DET = .05; see Table A for PP, max impulse=RF (Table B)*UI (Table C)

No delayed DET = .95, $B_\beta(.14, .30)*1E2+101$ kPa

DET = 0

Case 2

DF = .1 (.15)

DEF = .90 (.85)

Delayed DET .1, see Case 1

No delayed DET .90

FS=1m/s = .10, $B_\beta(.04, .75)*1E2+101$ kPa

FS=2m/s = .2, $B_\beta(.07, .75)*1E2+101$ kPa

FS=4m/s = .5, $B_\beta(.14, .75)*1E2+101$ kPa

FS=8m/s = .2, $B_\beta(.27, .75)*1E2+101$ kPa

DET = 0

Case 3

DF = .05 (.10)

DEF = .95 (.90)

Delayed DET = .05, see Case 1

No delayed DET = .95, $B_p(.19,30)*1E2+101$ kPa

DET = 0

Reformatting, the probability of the various modes of combustion is:

	<u>Case 1</u>	<u>Case 2</u>	<u>Case 3</u>
DF	.05	.10	.05
DEF	.9025	.81	.9025
DET	.0475	.09	.0475

For detonations, the following information is applicable:

Table A peak pressure after detonation:

Pressure(kPa)	150	175	200	225	250	275	300
Probability	0.0	.10	.40	.68	.85	.94	1.0

Table B reflection fraction of original wave:

Reflection Frac.	1	1.5	2.0	2.25	2.5	3.0
Probability	0.0	.10	.30	.50	.80	1.0

Table C maximum impulse of unreflected wave:

Max Impulse(kPa-s)	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
Probability	0.0	.05	.13	.25	.50	.75	.88	.95	1.0

For deflagrations, the dp is:

Case 1

<u>dp(kp)</u>	<u>Cumulative Probability</u>
1.34	0.00E-0
2.68	5.31E-4
5.37	1.44E-2
7.38	5.37E-2
8.72	9.99E-2
11.41	2.38E-1
14.09	4.14E-1
15.43	5.04E-1
17.45	6.29E-1
20.80	7.95E-1

Case 1 (Continued)

<u>dp(kp)</u>	<u>Cumulative Probability</u>
24.83	9.15E-1
27.51	9.57E-1
32.88	9.91E-1
39.59	9.99E-1
46.30	1.00E+0

Case 2

<u>dp(kp)</u>	<u>Cumulative Probability</u>				<u>Weighted Average</u>
	<u>1.0m/s</u>	<u>2.0m/s</u>	<u>4.0m/s</u>	<u>8.0m/s</u>	
0.00	0.00E-0	0.00E-0	0.00E-0	0.00E-0	0.00E-0
0.67	1.63E-3	0.00E-0	0.00E-0	0.00E-0	1.63E-4
1.34	1.86E-2	2.61E-4	0.00E-0	0.00E-0	1.91E-3
2.01	6.63E-2	2.44E-3	0.00E-0	0.00E-0	7.12E-3
2.68	1.47E-1	1.06E-2	0.00E-0	0.00E-0	1.68E-2
3.36	2.52E-1	3.00E-2	0.00E-0	0.00E-0	3.12E-2
4.70	4.85E-1	1.18E-1	2.00E-4	0.00E-0	7.22E-2
6.71	7.64E-1	3.62E-1	5.07E-3	0.00E-0	1.51E-1
8.72	9.11E-1	6.29E-1	3.74E-2	0.00E-0	2.36E-1
10.07	9.58E-1	7.68E-1	9.35E-2	0.00E-0	2.96E-1
12.75	9.92E-1	9.28E-1	3.10E-1	0.00E-0	4.39E-1
14.09	9.97E-1	9.63E-1	4.51E-1	2.41E-4	5.18E-1
16.10	9.99E-1	9.88E-1	6.56E-1	2.06E-3	6.26E-1
20.13	1.00E+0	9.99E-1	9.14E-1	4.05E-2	7.65E-1
22.14	1.00E+0	1.00E+0	9.64E-1	1.10E-1	8.04E-1
24.83	1.00E+0	1.00E+0	9.91E-1	2.83E-1	8.52E-1
27.51	1.00E+0	1.00E+0	9.98E-1	5.19E-1	9.03E-1
28.85	1.00E+0	1.00E+0	9.99E-1	6.37E-1	9.27E-1
30.20	1.00E+0	1.00E+0	1.00E+0	7.41E-1	9.48E-1
32.88	1.00E+0	1.00E+0	1.00E+0	8.90E-1	9.78E-1
34.89	1.00E+0	1.00E+0	1.00E+0	9.50E-1	9.90E-1
38.25	1.00E+0	1.00E+0	1.00E+0	9.90E-1	9.98E-1
42.28	1.00E+0	1.00E+0	1.00E+0	9.99E-1	1.00E-0
46.30	1.00E+0	1.00E+0	1.00E+0	1.00E+0	1.00E-0

Case 3

<u>dp(kp)</u>	<u>Cumulative Probability</u>
3.36	0.00E-0
5.37	8.72E-4
8.05	1.01E-2
10.74	4.65E-2
12.75	1.03E-1
15.43	2.22E-1
18.79	4.18E-1
20.13	5.01E-1
22.14	6.19E-1
26.17	8.07E-1
29.53	9.05E-1
32.21	9.51E-1
38.25	9.92E-1
44.29	9.99E-1
51.00	1.00E+0

Sources of Uncertainty

The major source of uncertainty was the wide envelope of initial conditions. A secondary source of uncertainty was the effect of flow patterns in the building and where hydrogen might build up.

Correlations with Other Variables

No correlations were specified by the Expert for this issue.

Suggested Methods for Reducing Uncertainty

No suggestions were made for reducing uncertainty.

5.4 Containment Loads Issue 4. Grand Gulf Containment Loads at Vessel Breach

Summary of Issue 4 Grand Gulf Containment Loads at Vessel Breach

Experts consulted: Louis Baker, Argonne National Laboratory; Ken Bergeron, Sandia National Laboratories; Ted Ginsberg, Brookhaven National Laboratory.

Issue Description

Considering the phenomena associated with vessel breach at Grand Gulf, what distributions characterize the uncertainty in the loads on containment structures? Three structures within the containment were considered:

1. The drywell;
2. The containment shell (assuming failure of the drywell or other mechanisms of suppression pool bypass); and
3. The RPV pedestal.

The peak quasi-static pressure experienced by each structure was to be quantified. For the drywell wall and the RPV pedestal, impulse resulting from explosive events (i.e., steam explosions) was also to be quantified.

Three cases were to be considered:

1. The RPV is at high pressure (6.9 to 7.6 MPa) before meltthrough of the bottom head. At least 230 m³ of water has accumulated on the drywell floor (a depth greater than 2 m in the pedestal) as a result of water overflow from the suppression pool.
2. The RPV is at low pressure (300 to 600 kPa) before meltthrough of the bottom head. At least 230 m³ of water has accumulated on the drywell floor.
3. The RPV is at high pressure (6.9 to 7.6 MPa) before meltthrough of the bottom head. The only water on the drywell floor is the 2 to 5 m³ in the sumps at the bottom of the pedestal.

The panel decided to consider the following variations on these basic cases:

- a. Zirconium oxidations: high (32%) and low (10%)
- b. Initial RPV hole size: large (2 m²) and small (0.1 m²)
- c. Melt fraction ejected: high (50%) and small (25%).

Other cases are possible for this issue (e.g., low-pressure RPV and no water on the drywell floor). The three cases above were selected by the analysts because they were assessed to have the greatest possibility of loading on containment structures and thus the greatest potential for risk significance.

Summary of Experts' Rationale/Methodology

EXPERT A.

Static Pressurization of the Drywell

Expert A based his assessment of the static pressure differential across the drywell for Cases 1 and 3 on the results of CONTAIN calculations that are published in NUREG/CR-4551, Volume 2, Part 5. He believed that the CONTAIN results represent estimates of the maximum possible pressure rise in the drywell for each set of initial and boundary conditions. The Expert felt that the reduction in the water level of the suppression pool (which was not considered by CONTAIN) would yield a shorter period for drywell pressurization (due to earlier clearing of the drywell vents) and ultimately would result in a lower peak pressure.

Expert A felt that the peak pressure in the drywell was proportional to the square root of the fraction of the core material that is ejected but was insensitive to the metallic content of the ejected debris (in the 10% to 50% in-vessel zirconium oxidation range). Peak pressure was also found to depend on the size of the hole in the vessel bottom through which blowdown occurred.

For the case where the RPV is at low pressure and there is water in the drywell, the Expert felt that fuel-coolant interaction (steam explosion) was the only mechanism for drywell pressurization. He felt that a significant explosion is prevented by the quenching of debris in a stratified configuration caused by structures below the RPV. This pressurization of the drywell would scale according to the ratio of the pedestal volume to the drywell volume.

Expert A felt that for all three cases, impulsive loading on either the drywell or the pedestal would be negligible.

Static Pressurization of the Containment

Expert A evaluated the peak pressurization of the containment by considering four combinations of boundary conditions based on two parameters arising from the in-vessel accident progression. The parameters were: the extent of in-vessel zirconium oxidation and the fraction of the core debris ejected. It was felt that the principal mechanism for the pressurization of the containment was the combustion of the hydrogen produced by oxidation of the unoxidized portion of the ejected metal. A 25% minimum oxidation of the unreacted zirconium (attributed to CONTAIN results) was considered. Burn completeness was assigned for each combination of in-vessel zirconium oxidized based on the Expert's knowledge of hydrogen combustion. Expert A stated that the peak pressure would be reduced if containment sprays were operating but did not quantify the extent of the reduction. He felt that the uncertainties in direct containment heating, steam explosions, and any other phenomena are covered by the greater uncertainty in the quantity of hydrogen produced.

Static Pressurization of the Pedestal

Expert A used the results of the CONTAIN calculations in assessing the pressurization of the pedestal for Cases 1 and 3. The pedestal pressure was considered to be determined mainly by two parameters, the rate of melt ejection and vessel blowdown, which are sensitive primarily to the size of the vessel breach. The peak pedestal pressures scale linearly with the fraction of the core affected and are independent of the quantity of unoxidized zirconium in the debris. The CONTAIN results identified Case 3 as having a lower peak pressure than Case 1, because the lack of water reduces the availability of steam for zirconium oxidation. The Expert viewed this as a rate-limited process with greater fractions of the core ejected and larger vessel breach sizes leading to higher rates. It was determined that adequate supplies of zirconium and steam for reaction were available for all circumstances considered.

For Case 2, molten core-coolant interaction (MCCI) was seen as the only source of high pressure. The Expert believed that a stratified interaction following the injection phase was possible. This interaction would be independent of the size of the vessel breach. The uncertainty in the peak pedestal pressure due to variations in the debris' zirconium content was considered small compared with the uncertainty in the yield of the debris-coolant interaction. The maximum steam explosion was considered to be 1% efficient with the compression of the gas in the pedestal taken as being isentropic. Berman's method in computing steam explosion efficiency was inverted to obtain the extent of debris participation. The assumed efficiency was varied up to the assumed maximum to represent uncertainty in peak pressure.

EXPERT B.

Expert B relied on his knowledge of containment loading phenomena coupled with relevant references to arrive at his distributions. For calculations, he used a CONTAIN study of the Grand Gulf containment response to high pressure reactor failures. He felt that the dominant sources of uncertainty were: (a) the lack of analyses of the events, (b) the lack of understanding of the combined HPME/FCI scenarios, and (c) for the peak containment pressure the artificiality of the requirement not to consider the combustion of pre-existing hydrogen (i.e., hydrogen released to the containment before vessel breach) in the containment at vessel breach.

Static Pressurization of the Drywell

Expert B felt that the pressurization of the drywell was not significantly affected by the amount of zirconium oxidation or the total amount of core debris. The important parameter (the only one the Expert considered) was the RPV hole size.

The Expert described Case 1 as a high pressure melt injection (HPME) which would result in drywell pressurization. He felt that the suppression pool vents would clear relatively early and that hydrogen burns were unlikely. The median value in his distribution was taken as the pressure rise

associated with the design basis accident (DBA). The low end of the range reflects the Expert's feeling that the precursor steam release would open the vents before a large amount of the core had been ejected, lowering the peak drywell pressure. For large RPV holes, the high end of the range accounts for the possibility of rapid source terms where the vents do not clear rapidly enough to reduce the drywell pressure. With small RPV holes, the source rate will be lower and it was felt that the vents would clear early enough to reduce the drywell pressure.

For Case 2, the Expert determined the dominant issue to be fuel coolant interaction. However, he felt that the debris/steam flow would become choked in the pedestal and the suppression pool vents would open before the drywell pressures became too high. Thus, he concluded that Case 3 could not be worse than Case 1.

For Case 3, the Expert relied on results from the CONTAIN calculations and determined that the drywell pressures would be approximately 20% higher for this case than for Case 1.

Static Pressurization of the Containment

For burns in the containment, Expert B considered only hydrogen released or generated at vessel breach. He also assumed that the containment sprays were not working. For Case 1, the only parameter of importance was the amount of core ejected. As the Expert felt that there would not be enough oxygen in the containment for burns after vessel breach, the median pressure value considers only the partial pressure of the noncondensibles. The low end of the pressure range accounts for the Expert's concern that the CONTAIN results, which were used to determine the median value, may have overestimated the pressure. The high end of the range reflects the Expert's belief that shallow coverage of the vents could yield significant suppression pool blowthrough.

For Case 2, the only significant parameter considered was the level of zirconium oxidation. Expert B felt that the only way to achieve a large pressure rise in the wetwell was to have a large FCI in the pedestal. The Expert did believe, however, that there will be some containment pressurization due to non-condensibles generated by the FCI. This represents the median of the Case 2 pressure distribution. The upper end accounts for the possibility of large FCIs. This base case was for subcases with large zirconium oxidation levels. For small amounts of zirconium oxidation, the Expert multiplied the base case by 1.8.

For the high pressure Cases 1 and 3, the Expert felt that the presence of water in the pedestal was not an important factor. Thus, the same distribution was used for both cases.

Static Pressurization of the Pedestal

CONTAIN results were used by Expert B as a starting point for Case 1 with high zirconium ejected, large RPV hole size and high melt fraction ejected. However, he felt that the zero slip assumption caused an exaggeration of the peak pedestal pressure. He reduced this value to obtain the peak

pedestal pressure. The low end of this distribution reflects the concern that a slower blowdown or more slip could occur than was assumed in the CONTAIN study. The high end includes the RPV plus extra pressure due to direct containment heating (DCH). For subcases where there was a small amount of core debris ejected, the results were reduced by 20%. Where a small RPV hole was considered, the results were reduced by 15%.

No available calculations were directly applicable to Case 2; however, the Expert felt that the pressures for this case would be less than those of Case 1. The distributions associated with the subcases based on Case 2 were obtained by multiplying the appropriate distributions from Case 1 by specific factors.

For Case 3 (dry cavity), the CONTAIN study indicated that the peak pedestal pressures were approximately 70% of the pedestal pressures associated with a wet cavity. Therefore, the Expert multiplied Case 1 distributions to obtain the Case 3 distributions.

Expert C.

The Expert considered the various phenomenologies that could be present in this issue. The phenomenologies considered were: (1) "early" melt-water and melt-atmosphere interactions; (2) melt jet breakup, mixing and fragmentation in the water; (3) steam generation before explosion; (4) direct containment heating (DCH); and (5) hydrogen burns in the drywell. The major sources of uncertainty identified by Expert B were: (1) the rate of vent uncover; (2) the rate of mixing, entrainment, etc.; (3) the rate of steam generation; and (4) the rate of hydrogen burn in the drywell.

The general procedure used was to get a "best guess" scenario, an upper and a lower bound scenario, use CONTAIN results to assess the reasonableness of the scenarios, and use best judgment to fill in the other cases.

The base case was constructed assuming the total mass participating was of secondary importance and only the short-term phenomena dominated, that the percent zirconium was a secondary effect, and that the percent hydrogen released before vessel breach gave a dp of 4 bars (best guess). The upper bound considered both short mixing times and larger percent mass participation, while the lower bound considered longer mixing times.

Method of Aggregation

Three experts were elicited for this issue. Experts A and B considered loads to the drywell structure, containment structure, and the RPV pedestal structure and provided distributions for all three cases. Expert C only considered loads to the drywell structure and only provided distributions for Cases 1 and 3. If the expert did not provide parameter values at the 0.0 and 1.0 fractiles, these values were obtained by linear extrapolation of the two closest points (provided the value obtained was physically possible). The experts considered variations on the basic three cases (they are referred to as subcases). If an Expert felt that a particular variation for a given case was not important, then the same distribution is

used for the subcases that arise from the variation. For a given subcase the experts' distributions were linearly averaged. If an expert did not provide distributions for a case then he was not considered for that case and only the distribution from the participating experts were aggregated.

The distributions provided by the experts for the various cases and subcases are listed in Tables 4-1 through 4-5 and are shown in Figures 4-1 through 4-8. In these tables and figures the various subcases are identified using the following characters:

- O: Large fraction of the zirconium was oxidized;
- o: Small fraction of the zirconium was oxidized;
- H: Initial RPV hole size was large;
- h: Initial RPV hole size was small;
- G: Large fraction of the melt is ejected;
- c: Small fraction of the melt is ejected.

Aggregated Results

Table 4-1
Aggregate Drywell Pressurization (Δp , bar)

Case 1				
<u>Probability</u>	<u>HC</u>	<u>Hc</u>	<u>hC</u>	<u>hc</u>
0.00	0.00	0.00	0.00	0.00
0.01	0.33	0.33	0.20	0.20
0.05	0.57	0.57	0.35	0.35
1.25	2.25	2.25	1.66	1.20
0.50	3.62	3.52	2.47	2.10
0.75	5.72	5.45	3.46	3.39
0.95	9.25	9.25	8.75	8.75
0.99	14.00	14.00	14.00	14.00
1.00	20.00	20.00	20.00	20.00

Case 2				
<u>Probability</u>	<u>HC</u>	<u>Hc</u>	<u>hC</u>	<u>hc</u>
0.00	0.00	0.00	0.00	0.00
0.01	0.30	0.11	0.17	0.11
0.05	0.32	0.16	0.27	0.15
0.25	0.44	0.35	0.39	0.31
0.50	1.62	1.62	0.85	0.85
0.75	3.97	3.97	2.70	2.70
0.95	8.75	8.75	8.50	8.50
0.99	14.00	14.00	14.00	14.00
1.00	20.00	20.00	20.00	20.00

Case 3

<u>Probability</u>	<u>HC</u>	<u>Hc</u>	<u>hC</u>	<u>hc</u>
0.00	0.33	0.33	0.20	0.20
0.01	0.39	0.39	0.24	0.24
0.05	0.60	0.60	0.36	0.36
0.25	2.07	1.80	1.30	1.30
0.50	3.49	3.13	2.50	2.27
0.75	5.60	4.53	3.43	3.04
0.95	8.01	6.89	4.44	3.98
0.99	9.10	8.19	4.97	4.91
1.00	9.50	8.85	5.31	5.31

Table 4-2
Aggregate Containment Pressurization (Δp , bar)

Cases 1 and 3				
<u>Probability</u>	<u>OC</u>	<u>Oc</u>	<u>oC</u>	<u>oc</u>
0.00	0.9	0.7	0.9	0.7
0.01	1.1	0.8	1.1	0.9
0.05	1.8	1.1	1.8	1.2
0.25	2.9	2.2	3.9	2.3
0.5	4.4	3.9	5.7	4.1
0.75	6.9	6.4	7.5	6.5
0.95	11.2	9.0	11.2	9.0
0.99	13.5	10.8	13.5	10.8
1.00	14.5	11.6	14.5	11.6

Table 4-3
Aggregate Containment Pressurization (Δp , bar)

Case 3				
<u>Probability</u>	<u>OH</u>	<u>Oh</u>	<u>oH</u>	<u>oh</u>
0.00	0.00	0.00	0.00	0.00
0.01	0.00	0.00	0.00	0.00
0.05	0.00	0.00	0.00	0.00
0.25	0.00	0.00	0.00	0.00
0.50	0.08	0.08	0.14	0.14
0.75	0.70	0.70	1.26	1.26
0.95	4.35	4.35	7.83	7.83
0.99	6.90	6.90	12.42	12.42
1.00	8.10	8.10	14.58	14.58

Table 4-4
Aggregate Pedestal Pressurization (Δp , bars)

Case 2								
Probability	<u>oHC</u>	<u>OHc</u>	<u>OhC</u>	<u>Ohc</u>	<u>oHC</u>	<u>oHc</u>	<u>ohC</u>	<u>ohc</u>
0.00	2.00	1.00	1.38	1.00	2.00	1.00	0.69	0.69
0.01	2.16	1.12	1.63	1.12	2.16	1.12	0.81	0.81
0.05	2.79	1.60	2.10	1.53	2.79	1.53	1.06	1.05
0.25	4.62	3.76	3.40	2.50	4.62	2.50	2.43	1.88
0.50	7.92	6.06	5.85	4.60	7.92	4.60	4.47	3.50
0.75	14.00	12.55	9.86	7.75	14.00	7.75	7.37	5.80
0.95	29.00	28.00	16.91	14.91	29.00	14.91	12.00	9.54
0.99	38.00	38.00	21.60	19.00	38.00	19.00	21.60	14.40
1.00	42.00	42.00	24.00	21.00	42.00	21.00	24.00	16.00

Table 4-5
Aggregate Pedestal Pressurization (Δp , bar)

Case 1				
Probability	<u>HG</u>	<u>Hc</u>	<u>hC</u>	<u>hc</u>
0.00	5.5	4.4	4.7	3.7
0.01	6.5	5.2	5.5	4.4
0.05	9.8	7.8	8.3	6.6
0.25	24.0	21.8	18.0	13.4
0.5	36.4	33.4	25.2	20.2
0.75	46.7	44.1	36.8	28.4
0.95	60.7	54.3	51.6	41.3
0.99	76.3	61.0	64.8	51.9
1.00	83.8	67.0	71.2	57.0

Case 3				
Probability	<u>HG</u>	<u>Hc</u>	<u>hC</u>	<u>hc</u>
0.00	3.8	3.1	0.0	2.6
0.01	4.5	3.6	0.6	3.1
0.05	6.8	5.5	3.0	4.6
0.25	20.5	16.8	8.3	8.1
0.50	31.6	28.6	16.2	12.9
0.75	42.5	40.7	23.9	19.2
0.95	52.4	50.0	36.2	28.9
0.99	58.2	58.0	45.4	36.3
1.00	60.0	60.0	49.8	39.9

Figure 4-1. Case 1 Grand Gulf Peak Drywell/Wetwell Differential Pressure at Vessel Breach. High RPV Pressure With Wet Cavity.

Figure 4-2. Case 2 Grand Gulf Peak Drywell/Wetwell Differential Pressure at Vessel Breach. Low RPV Pressure With Wet Cavity.

Figure 4-3. Case 3 Grand Gulf Peak Drywell/Wetwell Differential Pressure at Vessel Breach. High RPV Pressure With Dry Cavity.

Figure 4-4. Cases 1 and 3 Grand Gulf Peak Containment
Pressure at Vessel Breach. High RPV Pressure With Wet or Dry Cavity.

Figure 4-5. Case 2 Grand Gulf Peak Containment
Pressure at Vessel Breach. Low RPV Pressure With Wet Cavity.

Figure 4.6. Case 1 Grand Gulf Peak Pedestal Cavity Pressure at Vessel Breach.
High RPV Pressure With Wet Cavity.

Figure 4-7. Case 2 Grand Gulf Peak Pedestal Cavity Pressure at Vessel Breach.
Low RRV Pressure With Wet Cavity.

Figure 4-8. Case 3 Grand Gulf Peak Pedestal Cavity Pressure at Vessel Breach.
High RPV Pressure With Dry Cavity.

Individual Elicitations for Issue 4

Expert A's Elicitation

Issue 4. Grand Gulf Containment Loads at Vessel Breach

Description of Expert A's Rationale/Methodology

Static Pressurization of the Drywell

Expert A based his assessment of the static pressure differential across the drywell wall for Cases 1 and 3* on the results of CONTAIN calculations that were presented to the panel. However, he believed that the CONTAIN results provided estimates of the maximum possible pressure rise in the drywell for each set of initial and boundary conditions considered. This belief arose from the fact that reduction of the suppression pool level from nominal conditions, due to water overflow into the drywell, was not represented in the CONTAIN input. Expert A believed that this reduction in water level would lead to earlier clearing of the drywell vents than was predicted by CONTAIN. A shorter period for drywell pressurization between vessel breach and vent clearing would result in a lower peak pressure.

Expert A stated that the peak pressure in the drywell scales according to the square root of the fraction of the core material that is ejected. He felt that the peak pressure was insensitive to the metallic content of the ejected debris (within the range of 10 to 50% in-vessel zirconium oxidation). There would always be sufficient metal present in the debris to react, over the period of interest, with the available steam. Peak pressure was found to depend on the size of the hole in the vessel bottom through which blowdown occurred. This is because peak pressure is a strong function of the rate at which drywell pressurization occurs.

For Case 2* (low pressure RPV, water in the drywell), fuel-coolant interaction is the only possible mechanism for drywell pressurization. Expert A referred to this interaction as a steam explosion but said that impulsive loadings were negligible. A significant (i.e., coherent) explosion is prevented by the dispersal of debris by structures below the RPV. Quenching of the debris in a stratified configuration would occur, with little oxidation of the unreacted zirconium in the melt. Expert A stated that this situation would lead to drywell pressurization, that would scale according to the ratio of pedestal volume to drywell volume. Steam is compressed in the pedestal by the debris-coolant interaction and then expands isentropically into the drywell. These results are thus related to the pedestal pressurization results by the pedestal-to-drywell volume ratio.

Impulse Loadings

For all three cases, impulsive loading on either the drywell or pedestal walls was believed to be negligible. As stated above, in the low-pressure case (Case 2) the dispersal of debris flowing from the vessel by the

* Cases 2 and 3 have been reversed from what was presented in the original elicitation write-up for this expert.

control rod drive (CRD) housings and CRD support steel ("shoot-out steel") would prevent a coherent interaction. For the high-pressure ejection with water in the pedestal case (Case 1), Expert A believed that the dispersal of the water by high-velocity gas flows would prevent an explosive interaction between the melt and any water in the pedestal. No process that would create an explosive interaction can be identified for Case 3.

Static Pressurization of the Containment

Expert A evaluated the peak pressure in the containment for Cases 1 and 3* considering four different combinations of boundary conditions arising from the in-vessel accident progression. The two parameters were the extent of in-vessel zirconium oxidation and the fraction of the core debris that was ejected. Combustion of the hydrogen produced by oxidation of the unoxidized portion of the ejected zirconium metal was cited as the principal mechanism for expected pressurization of the containment. Oxidation of 25% of the unreacted zirconium and iron was the minimum considered, 100% oxidation was taken past the upper bound. The 25% minimum was attributed to CONTAIN code results. Expert A assigned a burn completeness for each combination of in-vessel zirconium oxidation, fraction of the core ejected, and percentage of in-vessel zirconium oxidized. Burn completeness was assigned based on the Expert's knowledge of hydrogen combustion. Figure A-1 shows Expert A's decomposition of this problem. Expert A stated that the peak pressure would be reduced if containment sprays were operating but did not quantify the extent of the reduction.

*Not considered uncertain in this elicitation.

Figure A-1. Containment Pressure Rise at Vessel Breach.

It was stated that pressure rise due to hydrogen burn was the dominant cause of containment pressurization. Uncertainties about direct containment heating, steam explosions, and any other phenomena are covered by the greater uncertainty in the quantity of hydrogen produced.

Static Pressurization of the Pedestal

Expert A based his assessment of the pressurization of the pedestal for Cases 1 and 3* on the results of the CONTAIN calculations mentioned above. Pedestal pressure was seen to be determined principally by the rate of melt ejection and vessel blowdown. These parameters are sensitive primarily to the size of the vessel breach (although the quantity of melt ejected is also dependent on the amount of debris that is molten when vessel breach occurs). Peak pedestal pressure scales linearly with the fraction of the core ejected and is independent of the quantity of unoxidized zirconium in the debris. In a comparison of Cases 1 and 3,* Expert A found Case 3* had reduced peak pressures. This reduction was based on the CONTAIN results. Presumably the lack of water reduces the availability of steam for zirconium oxidation. As for drywell pressurization, Expert A saw this as a rate-limited process. Greater fractions of the core ejected and larger vessel breach sizes lead to higher rates. Adequate supplies of zirconium and steam for reaction were assessed to be available in all circumstances considered.

For Case 2,* MCCI is the only source of high pressure. As discussed above, a major steam explosion was believed to be averted by the fragmentation and holdup of debris on the shoot-out steel. A stratified interaction following the injection phase was believed to be possible. This interaction would be independent of the size of the vessel breach since the ejection phase would be largely over. Expert A stated that the uncertainty in peak pedestal pressure caused by variations in the zirconium content of the debris is small in comparison with the uncertainty in the yield of the debris-coolant interaction. The maximum steam explosion was assumed by Expert A to be 1% efficient (i.e., 1% of the debris' thermal energy was assumed to do compression work on the steam in the pedestal). Compression of gas in the pedestal was taken as being isentropic. The method of Berman in computing steam explosion efficiencies was inverted to obtain the extent of debris participation. The thermal energy of the debris was considered to be 1.2 MJ/kg. The assumed efficiency was varied up to the assumed maximum to represent uncertainty in peak pressure.

Results of Expert A's Elicitation

Static Pressurization of the Drywell

Case 1: High-pressure ejection, water in pedestal.

The Expert's results are presented in Table A-1. These distributions are shown graphically in Figure A-2.

* Cases 2 and 3 have been reversed from what was presented in the original elicitation write-up for this expert.

Table A-1
Drywell Pressure Rise for Case 1
(bar)

Cum. Prob.	Breach Size (m ²)	0.1		2.0	
	Fraction of Core Ejected	33%	50%	33%	50%
0		1	1.5	2	2
0.5		1.5	2.3	3	3
0.9		2.5	3	5	6
1.0		3.5	4	7	9

*Close to base Case for the CONTAIN study.

Figure A-2. Peak Static Drywell/Wetwell Pressure Differential;
Case 1: High Pressure, Wet Pedestal.

Case 3*: High-pressure ejection, no water in pedestal.

The Expert's results are presented in Table A-2. These distributions are shown graphically in Figure A-3.

Table A-2
Drywell Pressure Rise for Case 3*
(bar)

Cum. Prob.	Breach Size (m ²)	0.1		2.0	
	Fraction of Core Ejected	33%	50%	33%	50%
0		1.3	1.7	1.5	2.5
0.5		2.7	3.0	3.5	4.0
0.9		3.3	4.0	5.0	7.5
1.0		4.0	5.0	7.5	9.5

Close to base case for the CONTAIN study.

Figure A-3. Drywell Peak Static Pressure; Case 3*:
High Pressure, Dry Pedestal.

Case 2*: Low-pressure ejection, water in pedestal.

The Expert's results are presented in Table A-3. These distributions are shown graphically in Figure A-4.

Table A-3
Drywell Pressure Rise for Case 2*

<u>Cumulative Probability</u>	<u>Fraction of Core Ejected</u>	
	<u>33%</u>	<u>50%</u>
0	0.1	0.13
0.5	0.3	0.4
0.9	0.4	0.5
1.0	0.5	0.7

Figure A-4. Drywell Peak Static Pressure; Case 2*:
Low Pressure, Wet Pedestal.

Static Pressure of the Containment

The Expert's results are provided in Table A-4. These distributions are shown graphically in Figure A-5.

Table A-4
Containment Pressure Rise for Cases 1 and 3*
(bar)

<u>In Vessel Zr Oxidation</u>		<u>10%</u>		<u>32%</u>	
<u>Cum. Prob.</u>	<u>Fraction of Core Ejected</u>	<u>33%</u>	<u>50%</u>	<u>33%</u>	<u>50%</u>
0.00		2.5	5.3	2.3	3.5
0.5		6.0	7.6	5.8	6.6
1.0		9.4	9.8	9.3	9.6

Figure A-5. Containment Pressure Rise; Cases 1 and 3*
High Pressure Ejection.

Static Pressurization of the Pedestal

Case 1: High-pressure ejection, water in pedestal

The Expert's results are presented in Table A-5. These distributions are shown graphically in Figure A-6.

Table A-5
Pedestal Pressurization for Case 1
(bar)

Breach Size (m ²)		0.1		
Cum. Prob.	Fraction of Core Ejected	33%	50%	2.0*
0		10	15	20
0.5		20	25	40
0.9		30	40	50
1.0		40	50	60

*For this breach size pedestal pressure depends more on vessel pressure than on the fraction of the core involved.

Figure A-6. Maximum Pedestal Pressure; Case 1:
High Pressure, Wet Pedestal.

Case 3*: High-pressure ejection, no water in pedestal.

The Expert's results are presented in Table A-6. These distributions are shown graphically in Figure A-7.

Table A-6
Pedestal Pressurization for Case 3*
(bar)

Cum. Prob.	Breach Size (m ²)	0.1		
		33%	50%	2.0*
0		5	10	20
0.5		12	15	40
0.9		20	25	50
1.0		25	35	60

*For this breach size pedestal pressure depends more on vessel pressure than on the fraction of the core involved.

Figure A-7. Maximum Pedestal Pressure; Case 3*:
High Pressure, Dry Pedestal.

Case 2*: Low-pressure ejection, water in pedestal.

The Expert's results are presented in Table A-7. These distributions are shown graphically in Figure A-8.

Table A-7
Pedestal Pressurization for Case 2*
(bar)

Cumulative Probability	Fraction of Core Ejected	
	33%	50%
0	1	2
0.5	4	6
0.9	8	12
1.0	16	24

Figure A-8. Maximum Pedestal Pressure; Case 2*:
Low Pressure, Wet Pedestal.

Sources of Uncertainty

Static Pressurization of the Drywell

The time at which the drywell vents cleared was believed to govern the uncertainty. Oxidation reactions in the pedestal were seen to be limited by reaction rates and choked flow. Vent clearing was assumed to arrest the pressure rise (as evidenced by calculated results) and thus be the key factor in determining peak pressure. For Cases 1* and 3*, the rate of zirconium oxidation in the pedestal was an additional uncertainty. For Case 2* the efficiency of the assumed steam explosion was seen to be the governing uncertainty.

Pressurization of the Containment

The quantity of hydrogen produced by oxidation of zirconium in the pedestal was identified as being the key uncertainty for Cases 1* and 3*. For Case 2*, steam explosion efficiency is controlling.

Pressurization of the Pedestal

The rate of vessel blowdown and thus the size of the vessel breach was identified as the key uncertainty for this quantity. However, in this elicitation the size of vessel breach was treated as a known parameter, supplied by the in-vessel expert group. Uncertainty in pedestal pressure, given the vessel blowdown rate, was governed by the residence time of the gas and particles in the pedestal. This, in turn, is governed by the flow rate of gas through the pedestal penetrations. Expert A believed these quantities were underestimated in the CONTAIN calculation. Therefore, uncertainty in the results was seen to be largely in the direction of being lower than the CONTAIN results.

For Case 2*, steam explosion efficiency was again identified as the governing uncertainty.

Expert B's Elicitation

Issue 4. Grand Gulf Containment Loads at Vessel Breach

Description of Expert B's Rationale/Methodology

The Expert's approach was to analyze and quantify two base cases and then to vary the base case distributions for each of the subcases. The subcases were parameter variations (i.e., zirconium oxidation, melt fraction ejected, and initial hole size) on the original three cases. The Expert used a five letter/number code to describe the cases. The first letter in the code denoted the plant, "G" for Grand Gulf, the second number referred to the case, and the last three letters identified the subcase. The three letters which identify the subcase have the following interpretations:

<u>Position</u>	<u>Description</u>	<u>Letter</u>	<u>Word</u>	<u>Nominal</u>	<u>Range</u>
First	Zirconium Oxidation	O	High	32%	> 21%
		o	Low	10%	< 21%
Second	RPV Hole Size	H	High	2 m ²	> 1 m ²
		h	Low	0.1 m ²	< 1 m ²
Third	Core Fraction Ejected	C	High	50%	> 33%
		c	Low	25%	< 33%

For example, case G1OHC is Case 1 with a high level of in-vessel zirconium oxidation, the core is ejected through a large hole in the RPV, and a large amount of core is ejected at vessel breach.

The two cases the Expert chose as base cases were G1OHC and G2OHC.

To arrive at his distributions, the Expert coupled his knowledge of containment loads phenomena with information he obtained from references relevant to this issue. For calculations, the Expert primarily relied on a CONTAIN study^{B-1} of the Grand Gulf containment response to high pressure reactor failures.

Results of Expert B's Elicitation

Impulse Loadings

It was decided that this panel would not include in their assessments the impulsive effects of ex-vessel steam explosions; therefore the Expert did not provide any assessments of impulse loadings.

However, it is interesting to note that the Expert considered impulse loadings to the drywell wall, from events in the drywell, unlikely. He felt that hydrogen detonations in the drywell were very unlikely and impulses from steam explosion in the pedestal cavity would be confined to the pedestal cavity region.

Static Pressurization of the Drywell

The Expert felt that pressurization of the drywell was controlled by phenomena that take place before the suppression pool vents clear. Furthermore, results presented in Reference B-1 indicated that hydrogen burns in the drywell do not significantly affect the drywell pressurization. Therefore, neither the amount of zirconium oxidation or the total amount of core debris is important. What is important is the RPV hole size because it affects the source rate (i.e., rate at which steam and core debris are ejected into the drywell). Thus, RPV hole size was the only parameter the Expert chose to consider for this loading.

The Expert described the first base case, G1OHC, as a high pressure melt ejection (HPME) which would result in drywell pressurization; however, the suppression pool vents would clear relatively early. The Expert felt hydrogen burns were unlikely for this case because of the high steam concentration in the drywell that would be coincident with this case. The Expert felt References B-1, B-2, and the NUREG-1150 Issue Paper "Pressure Rise at Vessel Breach at Grand Gulf" were relevant for this case. The Expert thought the drywell pressure differential would range from 0.3 to 7.1 bar. Reference B-2 likens HPME to a large break LOCA. The Expert chose the pressure rise associated with the design basis accident (DBA) as the median value in his distribution. However, the Expert felt the precursor steam release would open the vents before a large amount of the core had been ejected, which would tend to reduce the drywell pressure. The low end of the range reflects this rationale. The high end of the range accounts for the possibility of very rapid source terms (as assumed in Reference B-1) in which case the vents do not clear in time to effectively reduce the drywell pressure. Because RPV hole size is the only parameter being varied, this base case corresponds to the large RPV hole cases, G1xHz, where x and z refer to O or o and C or c, respectively. With a small RPV hole the source rate will be lower than for the large hole case. Because of the lower source rate, the Expert felt the vents would clear early enough to reduce the drywell pressure. For this set of cases, G1xHz, the Expert reduced the base case pressure by 40% to account for the vents opening.

For the second base case, G2OHC, the Expert thought References B-1 through and B-4 were relevant. In addition, NUREG-1150 Issue Paper "Pressure Rise at Vessel Breach at Grand Gulf" included information from the Grand Gulf final safety analysis report (FSAR). The dominant issue for this case was fuel coolant interaction (FCI). Drywell pressures cited in Reference B-3 ranged from 0.24 bar to 3.8 bar. Based on criticisms of Reference B-3 the Expert assumed these pressures were non-conservative. In addition, based on work presented in Reference B-1, the Expert felt the debris/steam flow would become choked in the pedestal and the suppression pool vents would open before the drywell pressures got too high. Thus, the Expert concluded that this base case could not be worse than the base case corresponding to Case 1. Therefore, the Expert reduced G1xHz by 0.1 bar to get G2xHz. For the small hole opening cases, G2xHz, the Expert multiplied G2OHC by 0.5 to account for the fact that a slow pour implies a smaller amount of debris would participate in an FCI and, therefore, only small steam explosion can occur with this case.

For Case 3, the Expert relied on results presented in Reference B-1 which indicated that drywell pressures are approximately 20% higher for the dry cavity case than for the wet cavity case. Therefore, the Expert multiplied the Case 1 distributions, G1xHz and G1xhz, by 1.2 to get the Case 3 distributions, G3xHz and G3xhz. The letters x and z correspond to 0 or o and C or c, respectively.

The results for Cases 1, 2, and 3 and their corresponding subcases are presented in Table B-1.

Table B-1
Peak Drywell Static Pressure (bar)
(relative to the containment)

Cases*	Cumulative Probability						
	0.01	0.05	0.25	0.50	0.75	0.95	0.99
G1xHz	0.30	0.40	0.80	1.80	4.00	6.00	7.10
G1xhz	0.18	0.24	0.48	1.08	2.40	3.60	4.26
G2xHz	0.30	0.40	0.70	1.80	3.90	5.90	7.00
G2xhz	0.15	0.20	0.35	0.90	1.95	2.95	3.50
G3xHz	0.36	0.48	0.96	2.16	4.80	7.20	8.52
G3xhz	0.22	0.29	0.58	1.30	2.88	4.32	5.11

* x = 0,o y = H,h z = C,c

Static Pressurization of the Containment

The pressure rise caused by burning hydrogen which was generated before vessel breach was addressed in another issue. Therefore, for burns in the containment the Expert only considered hydrogen which was released or generated at vessel breach. The Expert assumed that the containment sprays were not operating. However, the Expert did indicate that if the sprays were on, they would drastically reduce the pressure rise in the wetwell caused by a hydrogen burn.

For the first case the only parameter that the Expert considered important was the amount of core ejected. Case 5 in Reference B-1 indicated that approximately 1600 kg of hydrogen is produced at vessel breach. However, the Expert felt that pre-existing hydrogen would have been burned before vessel breach and, thus, there would not be sufficient oxygen in the containment for burns after vessel breach. Thus, for his median value, the Expert only considers the partial pressure of the non-condensibles in his assessment of the pressure rise. The Expert used results presented in Reference B-1 to estimate this pressure rise. The low end of the distribution accounts for the Expert's concern that the results in Reference B-1

may have overestimated the pressure rise. On the other hand, the high end of the range reflects the Expert's belief that the shallow coverage of the vents could lead to significant suppression pool blow-through. In addition, if some of the oxygen is still available in the wetwell, a hydrogen burn would result in a significantly higher pressure rise. For the cases with a small amount of core ejected, G1xyc, the Expert felt there was a reduced likelihood of combustion. Therefore, he reduced the base case distribution, G1xyc, by 20% to get the distribution for the small core ejection cases, G2xyc.

For Case 2, low pressure case, the level of zirconium oxidation was the only parameter that was considered significant. The Expert did not consider the RPV hole size a significant parameter for this case because he felt the pressure rise was determined either by combustion events or by accumulation of non-condensibles, neither of which is greatly influenced by the blowdown rate. The Expert felt that the only way to get a large pressure rise in the wetwell was to have a big FCI in the pedestal. The total amount of core debris ejected is not important because only a small amount of the debris participates in the steam explosion. The FCI would drive the non-condensibles into the wetwell. The Expert felt Reference B-1 was relevant because the mixing/heat transfer process could represent the FCI as well as a HPME. However, the Expert believes a gravity pour through the complex structure beneath the vessel will give premature FCIs and clear the pedestal of water. Thus, the Expert does not give much credibility to high entrainment fractions presented in Reference B-1. This reasoning leads to low drywell pressurization and not much suppression pool blow-through. The Expert believes there will be some containment pressurization due to non-condensibles generated by the FCI. This rationale represents median value in the base case distribution, G20HC. The high end of the distribution accounts for the possibility of large FCIs. Reference B-5 indicates that large amounts of hydrogen can be generated during an FCI. The upper end of the distribution includes combustion of this hydrogen. The base case is representative of cases with a large zirconium oxidation level, G20yz. For subcases with a small amount of zirconium oxidation, G20yz, the Expert multiplied the base case by 1.8 because with a low amount of zirconium oxidized in-vessel there is more available to be oxidized ex-vessel.

For the high pressure cases, Cases 1 and 3, the Expert did not feel the presence of water in the pedestal cavity was an important factor with regard to wetwell pressurization. Therefore, he used the same set of distributions to describe Case 3 as he did for Case 1.

The results for Cases 1, 2, and 3 and their corresponding subcases are presented in Table B-2.

Table B-2
Peak Containment Static Pressure (bar)

Cases*	Cumulative Probability						
	0.01	0.05	0.25	0.50	0.75	0.95	0.99
G1xyC	1.00	1.50	2.50	4.00	9.00	12.00	14.00
G1xyc	0.80	1.20	2.00	3.20	7.20	9.60	11.20
G2Oyz	0.10	0.20	0.40	0.70	2.10	5.10	7.50
G2oyz	0.18	0.36	0.72	1.26	3.78	9.18	13.50
G3xyC	1.00	1.50	2.50	4.00	9.00	12.00	14.00
G3xhc	0.80	1.20	2.00	3.20	7.20	9.60	11.20

* x = O,o y = H,h z = C,c

Static Pressurization of the Pedestal

The Expert used Reference B-1 as a starting point for the first base case, G1OHC. The Expert felt the credible cases presented in Reference B-1 were those with 50% of the core ejected with less than 50% entrained water. He thought Case 6^{B-1} (50% of the core ejected with 25% entrained water) was the most believable; however, he felt the zero slip assumption exaggerates the peak pedestal pressure. The peak pedestal pressure for Case 6^{B-1} was 37 bar. After a review of the relevant cases in Reference B-1, the Expert reduced the peak pedestal pressure by 7 bar to correct for slip. Thus, the Expert concluded that the median (.5) peak pedestal pressure would be 30 bar. Because the only analysis that was available to the Expert was Reference B-1, the Expert was concerned that there was some possibility that Reference B-1 overestimated the peak pressure. There could be a slower blow-down or more slip than what was assumed in the CONTAIN study. The low end of the distribution, 0.25, 0.5, and 0.01 fractiles, reflects this concern. On the other hand, a review of the relevant CONTAIN cases (Cases 1, 2, 3, 5, 6, 15) indicated the peak pressure is in the range of 40 to 50 bar. The Expert assigned to the 0.75 fractile a value of 48 bar. The Expert assigned the 0.95 fractile a value 65 bar because he felt there was some chance that the pedestal pressure would approach the reactor pressure. The very high end of the distribution, 80 bar at the 0.99 fractile, includes the RPV pressure plus some extra pressure due to direct containment heating (DCH) and FCI. For subcases where a small amount of core debris is ejected, G1xyc, the Expert reduced the base case by 20%. To account for the slow blow down associated with a small hole size, the Expert reduced the base case by 15% to get G1xhz. The breadth of these distributions reflects the sparse amount of information (primarily Reference B-1) available for the Expert to analyze.

There were no calculations that were directly applicable to Case 2. The Expert indicated that he had very little to work with and that some calculation should be done for this case. The Expert felt the pedestal pressures for this case would be less than the pressures obtained for Case 1. As a first estimate, the Expert multiplied the base distribution for Case 1, G10HC, by 0.5 to get the second base case distribution, G20HC. The Expert felt that with a large RPV hole size the amount of zirconium oxidation and the amount of core debris ejected were not important. Thus, the distribution used for the second base case was applied to subcases G20Hc and G20Hz. Subcase G20Hz was obtained by multiplying case G20HC by 0.5. The reason for this reduction was that the slower pour rate associated with the small RPV hole implied a smaller amount of debris would participate in FCI. Subcase G20Hc was also obtained by multiplying case G20HC by 0.5. Subcases G20hz were obtained by multiplying case G20Hz by 0.5.

The CONTAIN study²⁻¹ indicated that peak pedestal pressures associated with a dry cavity were approximately 70% of the pedestal pressure associated with a wet cavity. Therefore, the Expert multiplied the Case 1 distributions, G1xyz, by 0.7 to get the Case 3 distributions, G3xyz.

The results for Cases 1, 2, and 3 and their corresponding subcases are presented in Table B-3.

Table B-3
Peak Pedestal Static Pressure (bar)

Cases*	Cumulative Probability						
	0.01	0.05	0.25	0.50	0.75	0.95	0.99
G1xHC	6.00	8.00	15.00	30.00	48.00	65.00	80.00
G1xHc	4.80	6.40	12.00	24.00	38.40	52.00	64.00
G1xhC	5.10	6.80	12.75	25.50	40.80	55.25	68.00
G1xhc	4.08	5.44	10.20	20.40	32.64	44.20	54.40
G20Hz	3.00	4.00	5.00	11.00	20.00	32.00	40.00
G2oHC	3.00	4.00	5.00	11.00	20.00	32.00	40.00
G20hz	1.50	2.00	2.50	5.50	10.00	16.00	20.00
G2oHc	1.50	2.00	2.50	5.50	10.00	16.00	20.00
G2ohz	0.75	1.00	1.25	2.75	5.00	8.00	10.00
G3xHC	4.20	5.60	10.50	21.00	33.60	45.50	56.00
G3xHc	3.36	4.48	8.40	16.80	26.88	36.40	44.80
G3xhC	3.57	4.76	8.92	17.85	28.56	38.67	47.60
G3xhc	2.86	3.81	7.14	14.28	22.85	30.94	38.08

* x = O, o y = H, h z = C, c

Sources of Uncertainty

The Expert identified three factors that contributed to the uncertainty associated with this issue: (1) the absence or scarcity of careful analyses of the events; (2) the lack of understanding of combined HPME/FCI scenarios (it is a complex process and all the experiments have self-destructed); and (3) the artificiality of the requirement not to consider the combustion of pre-existing hydrogen (i.e., hydrogen released before vessel breach) in the containment at vessel breach.

REFERENCES

- B-1. K. K. Murata, "Parametric CONTAIN Calculations of the Containment Response of the Grand Gulf Plant," Sandia National Laboratories, Letter Report, February 15, 1988.
- B-2. R. J. Lipinski, "High Pressure Melt Ejection Effects in Grand Gulf," Appendix B to QUEST Study on Grand Gulf in "Uncertainty in Radionuclide Release Under Specific LWR Accident Conditions," Vol. IV, P. K. Mast et al., Sandia National Laboratories, SAND84-0410, December 1985.
- B-3. Letter, M. L. Corradini (University of Wisconsin) to A. S. Benjamin (Sandia National Laboratories), "Ex-vessel FCIs for Grand Gulf Risk Analysis," November 13, 1986.
- B-4. Memo, M. Berman (Sandia National Laboratories) to A. S. Benjamin (Sandia National Laboratories), "Ex-vessel FCIs for Grand Gulf Risk Analysis," December 10, 1986.
- B-5. B. Marshall, "Hydrogen Generation During Fuel-Coolant Interactions: Results from the FITS-D Series," SAND88-1335C, Sandia National Laboratories, June 1988.

Expert C's Elicitation

Issue 4. Grand Gulf Containment Loads at Vessel Breach

Description of Expert C's Rationale/Methodology

The Expert first considered the various phenomenologies that could be present in this situation. The phenomenologies considered were: (1) "early" melt-water and melt-atmosphere interactions such as steam explosions or FCIs and hydrogen burns; (2) melt jet breakup, mixing, and fragmentation in the water; (3) steam generation before explosion; (4) direct containment heating (DCH); (5) hydrogen burns in the drywell. The Expert decided that the major sources of uncertainty to consider were: (1) rate of vent uncover, (2) rate of mixing, entrainment, etc., (3) rate of steam generation, and (4) rate of hydrogen burn in the drywell.

The general procedure used was to get a "best guess" scenario, get a upper and a lower bound scenario; use CONTAIN results to assess the the reasonableness of the scenarios, and use best judgment to fill in other cases.

The base case was constructed assuming the total mass participating was of secondary importance and only the short-term phenomena dominated, that the percent of zirconium was a secondary effect, and that the percent of hydrogen released previous to vessel breach gave a dp of 4 bars (best guess). The upper bound considered both short mixing times and larger percent of mass participating, while the lower bound considered longer mixing times.

Results of Expert C's Elicitation

The Expert only gave results for the maximum drywell pressure and assumed water was present in all cases and the no-water case was not elicited.

The Expert defined 16 cases (listed in Table C-1) based on his decomposition for the important parameters: vessel pressure, percent of total core mass participating, size of vessel breach, and percent of total zirconium unoxidized. Water was assumed to be present in the drywell in all cases.

Table C-1
Definition of Cases

<u>Case</u>	<u>Pressure (psi)</u>	<u>Mass (%)</u>	<u>Size (m²)</u>	<u>% Zr (unoxidized)</u>
1	1000	50	.1	68
2	1000	50	.1	34
3	1000	50	2	68 worst
4	1000	50	2	34
5	1000	25	.1	68
6	1000	25	.1	34
7	1000	25	2	68
8	1000	25	2	34
9	100	50	.1	68
10	100	50	.1	34
11	100	50	2	68 base
12	100	50	2	34
13	100	25	.1	68
14	100	25	.1	34 best
15	100	25	2	68
16	100	25	2	34

For each of the cases the Expert gave a probability distribution for the pressure rise.

Table C-2
Probability Distributions Δp (bars)

<u>Case</u>	<u>Fractiles</u>						
	<u>0.0</u>	<u>0.05</u>	<u>0.25</u>	<u>0.5</u>	<u>0.75</u>	<u>0.95</u>	<u>1.0</u>
1	0	2	3	4	7.5	10	20
2	0	2	3	4	7.5	10	20
3	0	2	4	6	8.5	10	20
4	0	2	4	6	8.5	10	20
5	0	2	3	4	7.5	10	20
6	0	2	3	4	7.5	10	20
7	0	2	4	6	8.5	10	20
8	0	2	4	6	8.5	10	20

Table C-2 (continued)

<u>Case</u>	<u>Fractiles</u>						
	<u>0.0</u>	<u>0.05</u>	<u>0.25</u>	<u>0.5</u>	<u>0.75</u>	<u>0.95</u>	<u>1.0</u>
9	0	2	2.5	3	7	10	20
10	0	2	2.5	3	7	10	20
11	0	2	3	4	7.5	10	20
12	0	2	3	4	7.5	10	20
13	0	2	2.5	3	7	10	20
14	0	2	2.5	3	7	10	20
15	0	2	3	4	7.5	10	20
16	0	2	3	4	7.5	10	20

The Expert said to linearly interpolate and that all the cases were relatively close with secondary effects making up the differences. We can see from the results that the percent of zirconium unoxidized did not turn out to be a significant contributor to the differences.

The Expert did not give information on the impulse loading of the drywell wall, containment pressure rise, and maximum pressure and impulse to pedestal.

Correlations with Other Variables

We can see that the results are correlated to the output of the in-vessel issue on bottom head failure where the vessel pressure, percent of mass participating, size of the breach, and percent of zirconium unoxidized are specified.

Suggested Methods for Reducing Uncertainty

The major uncertainties are in the short-term phenomena. No explicit recommendation was made for reducing uncertainties.

5.5. Containment Loads Issue 5: Pressure Increment in the Sequoyah Containment at Vessel Breach

Summary of Expert Panel's Assessment of Issue 5
Pressure Increment in the Sequoyah Containment at Vessel Breach

Experts consulted: Ken Bergeron, Sandia National Laboratories; Ted Ginsberg, Brookhaven National Laboratory; Marty Plys, Fauske and Associates.

Issue Description

What distributions characterize the uncertainty in the pressure rise in containment at vessel breach for Sequoyah. This pressure rise may result from one or more of the following events:

1. Blowdown of the Reactor Coolant System (RCS);
2. Ex-Vessel Molten Core-Coolant Interactions (MCCI);
3. Hydrogen Combustion;
4. Direct Containment Heating (DCH).

RCS blowdown and DCH cause significant loads to the containment only if the RCS pressure is ten to twenty atmospheres or more above that of the containment at vessel breach.

The initial presentation of this issue delineated four RCS pressure ranges. When water in the cavity, sprays, and ice are considered, the case structure for Sequoyah is as follows:

<u>Case</u>	<u>RCS Pressure (psia)</u>	<u>Cavity Water</u>	<u>Sprays Operating</u>	<u>Ice Remaining</u>
1	2500	Wet	Either	Yes
1a	2500	Dry	No	Yes
1b	2500	Dry	No	No
2	2000	Wet	Either	Yes
2a	2000	Dry	No	Yes
2b	2000	Dry	No	No
3	500-1000	Wet	Either	Yes
3a	500-1000	Dry	No	Yes
3b	500-1000	Dry	No	No
4	15-200	Wet	Either	Yes
4a	15-200	Dry	No	Yes
4b	15-200	Dry	No	No

A wet cavity is defined as water up to the bottom head of the reactor vessel, which corresponds to a depth of 16 ft; the nominal depth assumed is 10 ft. For times when water is above the bottom head of the vessel, the

experts believed that the dispersal of corium into the containment will not occur; the pressure rise in the containment for this scenario was assumed to be similar to that of Case 4. In the original definition of the issue, it was stated that Cases 2, 2a, and 2b could have different in-vessel hydrogen production due to partial upper head injection (UHI) operation, but the differences in Cases 1, 1a, and 1b might be minimal. Since that time, the NRC has given Tennessee Valley Authority (TVA) permission to remove the UHI system from Sequoyah at the next refueling outage. The NRC also decided that it wished Sequoyah to be analyzed without UHI for this project.

The panel decided to consider the following variations on these basic cases:

Zr oxidation: high (60%) and low (25%);
 Melt fraction ejected: high (75%) and low (33%); and
 Initial hole size: large (2 m²) and small (0.1 m²).

Summary of Experts' Rationale/Methodology

Expert A relied heavily on the results of CONTAIN calculations, the results of the Surtsey Direct Containment Heating (DCH) experiments, and EPRI NP-5127. Expert A's judgment was that the CONTAIN calculations with unconditional hydrogen burn approximate an upper bound pressure rise for the following phenomenological reasons:

1. All debris is assumed in CONTAIN to be finely particulated and available for DCH upon entering the lower compartment. Realistically, some debris can enter the compartment in a wavelike manner and transfer much less energy to the atmosphere than predicted in CONTAIN. This phenomenon would also result in lower hydrogen generation rates than predicted in CONTAIN.
2. The presence of structures in the lower compartment and the geometry of the ice condenser inlets appear to preclude transport of significant quantities of debris into the ice condenser. Very little debris can be expected to enter the upper compartment. Since debris will be mostly confined to the lower compartment, heat transfer from debris will be limited by the high temperatures attained by the gas. Hydrogen generation will be limited by the availability of steam relative to cases in which debris can be transported outside the lower compartment. Expert A felt that CONTAIN overestimates the debris that would enter the upper compartment.

Expert A felt that the pressure rise at vessel breach could be decomposed into pre-burn and burn increments. The total pressure rise was expressed; therefore, as the product of the pressure rise ratio $(P_2/P_1)_{\text{sens}}$ due to sensible heating and the pressure rise ratio $(P_1/P_2)_{\text{burn}}$ as a result of hydrogen burns:

$$P_2/P_1 = (P_2/P_1)_{\text{sens}} * (P_1/P_2)_{\text{burn}}.$$

The sensible energy is a function of dispersal fraction and is sensitive to the assumption of particulate vs. film/wave dispersal. The hydrogen burn pressure rise varies for ejected core fractions between 20 and 40% and with dispersal time.

Expert A approached the problem by assessing specific cases and adjusting the results to obtain subcase assessments. The adjustments were based on sensitivities to the variables of hole size, presence of water in the cavity, and ice bypass. For Sequoyah, in-core oxidation was not considered, because it was considered to be insignificant as a sensitivity variable. It was Expert A's judgment that with respect to the reactor coolant system (RCS) pressure at vessel breach, there was no difference between 2000 psia and 2500 psia, given the other uncertainties involved with the issue. There is no probability of a detonation for any of the cases, because unconditional hydrogen burns take place as the hydrogen is being created.

Expert B approached the problem by using available CONTAIN, MAAP, and Surtsey results to carefully assess pressure rise distributions for six base cases. Using a PC spreadsheet program, he adjusted the six base cases to get values for the other 138 subcases required. The extremes of his ranges for the base cases were based on energy balance calculations. The best estimate is based on code results, primarily CONTAIN results and some subsequent calculations.

Expert B felt that a full cavity of water could either increase the pressure rise due to increased steam production, or decrease the pressure rise due to quenching. He expected the hot gases resulting from vessel breach at any pressure above a few hundred psia to result in ignition and complete combustion in any cell (volume) where a combustible mixture of hydrogen and oxygen is present. Some cells were not expected to burn due to lack of oxygen. Expert B concluded that detonations were unlikely.

At Sequoyah, when hydrogen ignition occurs before vessel breach, much of the hydrogen that was generated in-vessel is consumed. Expert B felt it was necessary to create an additional case-defining parameter to establish the containment hydrogen inventory at the time of vessel breach. Thus, the level of pre-existing hydrogen was added as an additional parameter to consider in the subcase definition.

Expert B considered Case 1 (2500 psia) and Case 2 (2000 psia) together as he thought there would be no appreciable differences between them. Factors other than the amount of pre-existing hydrogen, in-vessel zirconium oxidation, vessel hole size, and the fraction of mass ejected were accounted for by broadening the uncertainty bounds. In the course of this analysis, Expert B concluded that the pressure rise is fairly insensitive to the amount of in-vessel zirconium oxidation.

Expert C based the events he considered most likely to occur during pressurized melt ejection based on experiments and calculations. He believed that the DCH scenario involved large amounts of the core debris leaving the cavity in the form of small corium droplets. Suspension of the droplets allows for efficient and complete chemical reaction of the metals contained in the melt. High gas velocities from the cavity into the

containment are expected. Two 90° turns are required for the entrained debris droplets to make before entering the ice condenser. It is expected that the droplets will be trapped before entering the ice condenser, but steam and high temperature hydrogen will be transported through the ice condenser. Expert C believes the high temperature hydrogen will ignite when admitted into the upper containment, where oxygen is available.

The Expert based his "best estimates" on CONTAIN calculations and on scaled experiments of the very similar Watts Bar containment. He based the high side of his distributions on a steam blowdown scenario which optimized entrainment and burned the remaining iron. The low side of his distributions considered phenomena which might reduce pressure, e.g., larger drop diameter, or faster trapping.

Dependence on extent of zirconium oxidation, vessel breach area, and fraction of melt ejected were also considered. CONTAIN calculations had indicated that there was little dependence on previous zirconium oxidation. Expert C felt that the reason for low dependence on previous zirconium oxidation was oxygen starvation in the cavity. Cavity water can either enhance or reduce the pressure rise. The effect of a larger hole in the RPV increases the pressure increment because the gas would exit with higher velocity.

Method of Aggregation

All the experts determined that Cases 1 and 2 could be represented by the same distribution and so Case 2 is not reported. All three experts provided distributions for Cases 1, 3, and 4 in which the ice is fully functional. There were differing levels of participation, however, in providing separate distributions for the different subcases. Only Expert A provided separate distributions for different pre-existing levels of H₂. For the different subcases in which the ice is functional and the experts did not provide distributions, the distributions for higher level cases were replicated for experts not participating.

Only Experts A and B provided distributions for Cases 1, 3, and 4 in which the ice is not functional. Thus, only two distributions were aggregated. Again, higher level case distributions were replicated for unsupplied subcase distributions, if necessary. Using the ANOVA method for reducing case structure, 45 subcases for times in which the ice is functional were reduced to 25 subcases and for times in which the ice is not functional, 15 subcases were reduced to 9 subcases.

Aggregated Results

Aggregated results are given in Tables 5-1 and 5-2 and in associated Figures 5-1 through 5-20.

Table 5-1
Aggregate for Low Pressure or Non-HPME Cases

<u>Curve</u>	<u>Press</u>	<u>Core F</u>	<u>Ice</u>	<u>Hole</u>	<u>Cavity</u>	<u>Prex-H₂</u>	<u>Zr_{ox}</u>
1	-	-	Y	-	Deep	-	-
2	-	-	N	-	Deep	-	-
3	Low	-	Y	-	Wet	Low	-
4	Low	-	Y	-	Wet	High	-
5	Low	-	Y	-	Dry	Low	-
6	Low	-	Y	-	Dry	High	-
7	Low	-	N	-	Dry	Low	-
8	Low	-	N	-	Dry	High	-
9	Low	-	N	-	Wet	Low	-
10	Low	-	N	-	Wet	High	-

Table 5-1 (continued)
Low Pressure or Non HPME Cases
Pressure Rise (kPa)

<u>Curve</u>	<u>Cumulative Distribution Fractile</u>								
	<u>0%</u>	<u>1%</u>	<u>5%</u>	<u>25%</u>	<u>50%</u>	<u>75%</u>	<u>95%</u>	<u>98%</u>	<u>100%</u>
1	3.8	15.0	60.0	180.0	280.0	330.0	370.0	400.0	407.5
2	3.8	15.0	60.0	205.0	330.0	405.0	470.0	525.0	538.8
3	8.1	18.7	61.0	64.0	78.1	106.7	303.7	353.1	365.5
4	80.0	80.8	80.0	80.0	105.0	355.8	1240.0	1325.0	1346.3
5	4.8	8.3	12.5	30.0	64.8	74.3	93.3	122.5	129.8
6	12.0	16.7	35.7	59.8	74.2	238.3	808.7	927.5	957.7
7	4.1	8.3	15.0	50.0	82.5	75.0	112.0	142.5	150.1
8	10.7	16.7	40.8	60.4	75.2	311.8	1202.5	1325.0	1355.8
9	8.8	20.8	67.1	75.8	87.0	216.4	334.1	388.4	402.0
10	88.0	88.0	88.8	88.0	115.5	301.4	1384.0	1457.5	1480.8

Figure 5-1. Cavity Deeply Flooded; Above the Bottomhead of the Vessel (Curves 1 & 2).

Figure 5-2. RCS Low Pressure; Less Than 200 psia (Curves 3 & 4).

Figure 5-3. RCS Low Pressure; Less Than 200 psia (Curves 5 & 6).

Figure 5-4. RCS Low Pressure; Less Than 200 psia (Curves 7 & 8).

Figure 5-5. RCS Low Pressure; Less Than 200 psia (Curves 9 & 10).

Table 5-2
Aggregate for Intermediate Pressure Cases

<u>Curve</u>	<u>Press</u>	<u>Core F</u>	<u>Ice</u>	<u>Hole</u>	<u>Cavity</u>	<u>Prex-H₂</u>	<u>Zr ox</u>
1	Int.	High	Y	--	Wet	Low	--
2	Int.	Med.	Y	--	Wet	Low	--
3	Int.	Low	Y	--	Wet	Low	--
4	Int.	High	Y	Lrg.	Dry	Low	--
5	Int.	Med.	Y	Lrg.	Dry	Low	--
6	Int.	Low	Y	Lrg.	Dry	Low	--
7	Int.	High	Y	Sm.	Dry	Low	--
8	Int.	Med.	Y	Sm.	Dry	Low	--
9	Int.	Low	Y	Sm.	Dry	Low	--
10	Int.	High	Y	Lrg.	Wet	High	--
11	Int.	Med.	y	--	Wet	High	--
12	Int.	Low	y	--	Wet	High	--
13	Int.	High	Y	Sm.	Wet	High	High
14	Int.	High	Y	Sm.	Wet	High	Low
15	Int.	High	Y	Lrg.	Dry	High	High
16	Int.	Med.	Y	Lrg.	Dry	High	High
17	Int.	Low	Y	Lrg.	Dry	High	High
18	Int.	High	Y	Lrg.	Dry	High	Low
19	Int.	Med.	Y	Lrg.	Dry	High	Low
20	Int.	Low	Y	Lrg.	Dry	High	Low
21	Int.	High	Y	Sm.	Dry	High	--
22	Int.	Med.	Y	Sm.	Dry	High	--
23	Int.	Low	Y	Sm.	Dry	High	--
24	Int.	High	N	--	Dry	Low	--
25	Int.	Med.	N	--	Dry	Low	--
26	Int.	Low	N	--	Dry	Low	--
27	Int.	High	N	Lrg.	Dry	High	--
28	Int.	Med.	N	--	Dry	High	--
29	Int.	Low	N	--	Dry	High	--
30	Int.	High	N	Sm.	Dry	High	High
31	Int.	High	N	Sm.	Dry	High	Low

Table 5-2 (continued)

Curve	Cumulative Distribution Fractile								
	0%	1%	5%	25%	50%	75%	95%	99%	100%
1	34.0	38.9	58.7	126.5	225.6	459.6	720.0	819.4	844.3
2	22.6	27.8	48.5	107.3	182.4	321.2	534.8	608.3	626.7
3	15.4	23.3	34.8	88.2	130.8	259.0	419.2	480.7	496.1
4	37.8	46.9	83.3	241.7	384.4	496.8	687.4	916.3	971.0
5	23.1	31.3	56.3	194.2	294.0	375.8	516.2	621.4	647.2
6	14.9	18.8	34.4	112.1	179.4	225.1	305.9	372.0	388.5
7	30.0	37.5	67.5	177.7	301.3	404.5	610.6	746.4	780.3
8	20.0	25.0	45.0	139.2	226.2	299.2	462.2	512.7	525.3
9	12.4	15.7	28.8	84.8	143.5	188.8	277.8	317.6	327.8
10	45.9	51.8	75.8	171.7	284.5	543.2	765.0	928.6	968.5
11	43.5	47.6	64.1	130.2	201.6	355.8	540.4	632.1	655.0
12	25.8	33.2	62.6	99.6	149.4	276.3	422.1	482.8	510.2
13	45.8	50.8	70.8	144.8	259.2	481.8	700.5	864.8	905.8
14	43.9	50.3	67.8	135.7	227.4	485.9	668.8	847.7	884.9
15	95.5	108.4	150.0	288.5	412.6	532.2	728.7	954.4	1010.8
16	88.7	97.6	133.3	235.3	318.0	390.3	525.0	682.8	723.5
17	46.7	52.0	72.8	132.8	191.4	232.3	309.2	403.2	426.7
18	67.8	80.1	130.1	286.7	405.7	528.4	727.5	943.6	997.8
19	32.9	45.0	93.5	209.9	304.1	382.6	522.7	662.5	697.3
20	18.8	25.7	55.0	120.8	184.5	228.5	308.8	392.5	413.6
21	56.8	70.2	123.6	218.9	325.0	431.8	628.8	781.8	795.7
22	34.0	47.0	99.1	159.6	243.1	309.5	467.8	543.8	562.8
23	19.4	26.7	55.6	84.8	154.0	191.9	280.6	339.2	346.3
24	25.7	37.5	84.8	253.4	439.8	675.3	1090.8	1207.3	1236.4
25	17.0	25.0	57.1	101.2	316.7	462.7	651.2	824.3	847.6
26	10.6	15.7	36.1	120.6	189.6	276.9	471.6	533.4	548.9
27	50.8	72.3	158.4	341.6	597.3	764.9	1117.8	1226.7	1254.0
28	24.7	44.6	124.2	253.9	383.0	518.8	831.1	924.2	947.5
29	14.4	25.5	59.6	152.0	222.8	296.9	471.6	533.4	548.8
30	81.1	98.2	186.5	345.4	562.1	710.0	1085.5	1206.1	1236.3
31	32.3	54.3	142.4	313.9	502.1	689.4	1084.3	1208.1	1236.6

Figure 5-6. RCS Intermediate Pressure: 500 to 1000 psia (Curves 1, 2, 3).

Figure 5-7. RCS Intermediate Pressure: 500 to 1000 psia (Curves 4, 5, 6)

Figure 5-8. RCS Intermediate Pressure: 500 to 1000 psia
(Curves 7, 8, 9).

Figure 5-9. RCS Intermediate Pressure: 500 to 1000 psia
(Curves 10, 11, 12).

Figure 5-10. RCS Intermediate Pressure: 500 to 1000 psia (Curves 13, 14).

Figure 5-11. RCS Intermediate Pressure: 500 to 1000 psia (Curves 15, 16, 17).

Figure 5-12. RCS Intermediate Pressure: 500 to 1000 psia
(Curves 18, 19, 20).

Figure 5-13. RCS Intermediate Pressure: 500 to 1000 psia
(Curves 21, 22, 23).

Figure 5-14. RCS Intermediate Pressure: 500 to 1000 psia
(Curves 24, 25, 26).

Figure 5-15. RCS Intermediate Pressure: 500 to 1000 psia
(Curves 27, 28, 29).

Figure 5-16. RCS Intermediate Pressure: 500 to 1000 psia
(Curves 30, 31).

Table 5-3
Aggregate for High Pressure Cases

Curve	Press	Core F	Ice	Hole	Cavity	Prex-H ₂	Zr ox
1	High	High	Y	--	Wet	--	--
2	High	Med.	Y	--	Wet	--	--
3	High	Low	Y	--	Wet	--	--
4	High	High	Y	Lrg.	Dry	--	--
5	High	Med.	Y	Lrg.	Dry	--	--
6	High	Low	Y	Lrg.	Dry	--	--
7	High	High	Y	Sm.	Dry	--	--
8	High	Med.	Y	Sm.	Dry	--	--
9	High	Low	Y	Sm.	Dry	--	--
10	High	High	N	--	Dry	--	--
11	High	Med.	N	--	Dry	--	--
12	High	Low	N	--	Dry	--	--

Table 5-3 (Continued)
High Pressure Cases
Pressure Rise (kPa)

Curve	Cumulative Distribution Fractile								
	0%	1%	5%	25%	50%	75%	95%	99%	100%
1	46.4	53.5	81.6	173.5	287.7	537.5	814.8	1021.5	1073.1
2	44.8	51.1	76.5	147.7	238.4	413.5	588.8	712.5	748.8
3	26.4	34.8	66.8	108.4	158.8	303.1	451.3	532.4	553.2
4	86.0	112.5	178.4	308.7	416.2	552.7	886.8	1068.8	1118.7
5	61.4	75.0	129.6	232.0	317.1	427.1	587.3	712.5	743.8
6	33.1	40.7	71.1	131.0	191.0	250.7	340.3	417.5	438.8
7	72.0	80.8	102.1	236.3	318.8	435.7	708.8	855.0	881.3
8	46.0	60.0	116.2	176.0	242.2	318.2	485.6	570.0	588.6
9	25.4	33.2	64.4	103.0	153.5	195.3	284.5	346.3	358.2
10	48.8	63.4	217.8	427.4	619.6	835.4	1138.4	1248.9	1276.5
11	32.1	53.8	149.7	327.8	433.5	581.1	848.8	826.0	845.3
12	18.1	31.0	82.4	168.8	248.0	333.1	488.5	534.3	547.7

Figure 5-17. RCS High Pressure: 2000 to 2500 psia (Curves 1, 2, 3).

Figure 5-18. RCS High Pressure: 2000 to 2500 psia (Curves 4, 5, 6).

Figure 5-19. RCS High Pressure: 2000 to 2500 psia (Curves 7, 8, 9).

Figure 5-20. RCS High Pressure: 2000 to 2500 psia (Curves 10, 11, 12).

Individual Elicitations for Issue 5

Expert A's Elicitation

Issue 5: Pressure Increment in the Sequoyah Containment at Vessel Breach

Description of Expert A's Rationale/Methodology

Expert A used References A-1 to A-17, with main emphasis for the issue quantification on NUREG/CR-4896^{A-1} and its update,^{*} EPRI NP-5127,^{A-2} and results of the Surtsey DCH experiments.^{A-3 to A-6} Although there were some calculations for reference or extrapolation to most of the subcases, there was usually only one calculation and no data. This necessitated that judgment be used for effects of variations in explicit critical parameters in order to determine distributions for the subcases.

Expert A's judgment was that the CONTAIN calculations with unconditional hydrogen burn approximate an upper bound pressure rise for the following phenomenological reasons:

1. All debris is assumed to be finely particulated and available for DCH upon entering the lower compartment; however, some debris can enter the compartment in a wavelike manner and transfer little energy to the atmosphere;
2. As a consequence of the previous reason, hydrogen generation is lower when interactions with the atmosphere are limited;
3. The presence of structures in the lower compartment and the geometry of the ice condenser inlets appear to preclude transport of significant quantities of debris into the ice condenser;
4. As a consequence of the previous reason, very little debris can be expected to enter the upper compartment; and
5. Since debris will be mostly confined to the lower compartment, heat transfer from debris will be limited by the high temperatures attained by the gas and hydrogen generation will be limited by the availability of steam relative to cases in which debris can be transported outside the lower compartment.

Expert A noted that updated calculations⁴ with a 9-cell model of Sequoyah lead to lower pressures than those presented in Reference A-1. Thus, the Reference A-1 calculations appear to provide an upper bound for DCH predictions. Also mentioned in the update were improvements to the ice condenser heat transfer model leading to a peak pressure reduction of about 1.0 atm as compared to that of Reference A-1.

^{*}J. L. Tills, "An Update on Direct Containment Heating for Ice Condenser Plants," Sandia National Laboratories, Albuquerque, NM, 1988.

Expert A noted a pattern exhibited in the calculations, that demonstrated that the pressure rise at vessel breach was decomposable into pre-burn and burn increments. The total pressure rise was expressed, therefore, as the product of the pressure rise ratio $(P_2/P_1)_{\text{sens}}$ due to sensible heating and the pressure rise ratio $(P_2/P_1)_{\text{burn}}$ as a result of hydrogen burns:

$$P_2/P_1 = (P_2/P_1)_{\text{sens}} * (P_2/P_1)_{\text{burn}} \quad (1)$$

The sensible energy is a function of dispersal fraction and is sensitive to the assumption of particulate vs. film/wave dispersal. The hydrogen burn pressure rise varies for ejected core fractions between 20% and 40% and also with dispersal time. The assessment of Expert A was provided in terms of pressure rise ratios, and the initial pressure P_1 was always assumed to be 1.5 bar for the quantification of the issue.

The problem was approached with "base case" assessments, then the results were adjusted in order to obtain the subcase assessments. The adjustments were based on sensitivities to the variables of hole size, presence of water in the cavity, and ice bypass. For Sequoyah, in-core oxidation was not considered, because it was considered to be insignificant as a sensitivity variable. The effect of core fraction is incorporated as a variable in the determination of the pressure rise ratios, and was therefore considered inherently in the distributions provided.

It was Expert A's judgment that with respect to RCS pressure at vessel breach, there was no difference between 2000 psia and 2500 psia, given the other uncertainty involved with the issue. Thus, the results for cases 1 and 2 are provided together. A "base case" was presented for cases 1a and 2a, i.e., with high pressure, a dry cavity, ice present, and a small hole (penetration failure) at vessel breach. A "base case" was also presented for Case 3a, with intermediate pressure, a dry cavity, ice present, and a small hole at vessel breach. Distributions were not provided for Case 4, because the RCS pressure is too low to disperse significant (if any) debris. The upper bound was specified as the 99% percentile and the lower bound was specified as the 1 percentile.

Base Cases 1a and 2a

Expert A obtained the factors in Equation (1) above as follows. From Reference A-18, considering 75% of the core, the sensible pressure rise ratio is $3.0/1.5 = 2.0$ and the ratio after the burn is $6.0/3.0 = 2.0$. A prompt pressure increase to about 2.5 atm can be attributed mostly to vessel blowdown, and is independent of the amount of debris ejected. Therefore, an expression which accounts for the fraction f of debris participating is:

$$(P_2/P_1)_{\text{sens}} = 1.5 + (2.0-1.5)*f/0.75 \quad (2)$$

When $f = 0$, $P_2 = 2.25$ is recovered, and when $f = 0.75$, $P_2 = 3.0$ is recovered. Expression (2) is taken as the median. In forming the upper and lower bounds, the value of 1.5 is fixed because it is associated with

the blowdown. The slope of the equation below the median is decreased and the slope of the equation above the median is increased. The lower bound slope multiplier is 0.75:

$$(P_2/P_1)_{\text{sens}} = 1.5 + (2.0-1.5)*f*0.75/0.75 \quad (3)$$

and the upper bound slope multiplier is 1.25:

$$(P_2/P_1)_{\text{sens}} = 1.5 + (2.0-1.5)/f*1.25/0.75. \quad (4)$$

The median for the burn pressure rise for core fractions greater than 0.4 is taken from the 9-cell case in Reference A-18, $5.0/3.4 = 1.5$. However, there is a threshold effect for the onset of hydrogen generation and burning as seen from Reference A-18 and mentioned above. The burn pressure rise ratio also depends on the fraction of debris ejected. The median value for the distribution is as follows:

$$(P_f/P_2)_{\text{burn}} = \begin{cases} 1.0, & f \leq 0.2 \\ (1.0 + 0.5/0.2 * (f-0.2)), & 0.2 < f \leq 0.4 \\ 1.5, & f > 0.4 \end{cases} \quad (5)$$

The value of .2 is a threshold for sufficient hydrogen production. The lower bound of the distribution is:

$$(P_f/P_2)_{\text{burn}} = \begin{cases} 1.0, & f \leq 0.3 \\ (1.0 + 0.25/0.1 * (f-0.3)), & 0.3 < f \leq 0.4 \\ 1.25, & f > 0.4 \end{cases} \quad (6)$$

The upper bound ratio is taken from the 3-cell case as derived above:

$$(P_f/P_2)_{\text{burn}} = \begin{cases} 1.0, & f \leq 0.1 \\ (1.0 + 1./0.3 * (f-0.1)), & 0.1 < f \leq 0.4 \\ 2.0, & f > 0.4 \end{cases} \quad (7)$$

There is no probability of a detonation for any of the cases, because unconditional hydrogen burns take place as the hydrogen is being created.

Base Case 3a

For Case 3a, in which the RCS is at intermediate pressure, the adjustment factor g accounts for the lesser quantity of debris which may participate in DCH, and the greater propensity for wavelike versus particulate dispersal in the lower compartment. The burn factor in equation (1) is multiplied by g directly because hydrogen generation will scale by direct proportion to the amount of debris interacting in the lower compartment. The factor g is applied to the slope of the sensible heating multiplier. Therefore, the hydrogen burn ratio expressions above in (5), (6), and (7) are recast as:

Median:

$$P_f/P_2)_{\text{burn}} = \begin{cases} 1.0, & f \leq 0.2 \\ (1.0 + 0.5/0.2 * (f-0.2)*g, & 0.2 < f \leq 0.4 \\ 1.0 + 0.5*g, & f > 0.4 \end{cases} \quad (8)$$

Lower bound:

$$P_f/P_2)_{\text{burn}} = \begin{cases} 1.0, & f \leq 0.3 \\ (1.0 + 0.25/0.1 * (f-0.3)*g, & 0.3 < f \leq 0.4 \\ 1.0 + 0.25*g, & f > 0.4 \end{cases} \quad (9)$$

Upper bound:

$$P_f/P_2)_{\text{burn}} = \begin{cases} 1.0, & f \leq 0.1 \\ (1.0 + 1./0.3 * (f-0.1)*g, & 0.1 < f \leq 0.4 \\ 1.0 + 1.0*g, & f > 0.4 \end{cases} \quad (10)$$

The sensible heat expressions are equations (2), (3), and (4) recast as:

Median:

$$(P_2/P_1)_{\text{sens}} = 1.5 + (2.0-1.5)/0.75 * f*g \quad (11)$$

Lower Bound:

$$(P_2/P_1)_{\text{sens}} = 1.5 + (2.0-1.5)/0.75 * f*0.75*g \quad (12)$$

Upper Bound:

$$(P_2/P_1)_{\text{sens}} = 1.5 + (2.0-1.5)/0.75 * f*1.25*g \quad (13)$$

The distribution on g is considered uniform for $0.5 \leq g \leq 1.0$, and is correlated with the distributions on the pressure rise ratios with a correlation coefficient of 1.0. The lower bound for g is 0.5 because some DCH is credited or a lower initial vessel pressure of 1000 psi, and its upper bound cannot exceed unity because Case 3 pressures must never exceed Case 1 pressures.

Base Case Example Calculations

An example calculation is presented for Case 1a (and 2a) with high RPV pressure, dry cavity, and a small vessel hole size. Consider $f = 0.75$, i.e., 75% of the core is ejected. The median (50th percentile) sensible pressure rise factor is $1.5 + 0.666 * (0.75) = 2.0$, the burn factor is 1.50, and the initial pressure is 1.5 bar always, so:

$$P_c(\text{case 1a, } f = 0.75, 50\% \text{ percentile}) = 1.5 * 2.0 * 1.5 = 4.5 \text{ bar} \quad (a)$$

which is about 0.5 bar lower than the Reference 18 9-cell calculation. The maximum is given by considering $f = 1.0$ and using the upper bound. The sensible rise factor is $1.5 + 0.666 * 1.0 * 1.25 = 2.333$, the burn factor is 2.0, so:

$$P_1(\text{case 1a, } f = 1.0, 99 \text{ percentile}) = 1.5 * 2.33 * 2.0 = 7.0 \text{ bar.} \quad (\text{b})$$

Note that the maximum value for Case 3a with intermediate RPV pressure, dry cavity and a small vessel hole size cannot exceed the value for Case 1a, since an upper limit is given by $g = 1.0$. The median of the distribution for g in Case 3a is given by $g = 0.75$. Considering that $f = 0.75$ to compare with example (a), the median for sensible heat factor is $1.5 + 0.666 + 0.75 * 0.75 = 1.88$, the burn factor is $1.0 + 0.5 * 0.75 = 1.375$, so

$$P_1(\text{case 3a, } f = .75, 50 \text{ percentile}) = 1.5 * 1.88 * 1.375 = 3.87 \text{ bar.} \quad (\text{c})$$

Subcase Assessment

Among the sensitivity variables to consider for influencing pressure rises at vessel breach are: oxidation fraction, core fraction ejected, hole size, water in cavity, and ice bypass. Expert A believed that oxidation fraction was the least significant variable, and omitted this to reduce the number of variables. The dependency on core fraction ejected was already given above. Adjustments were therefore provided for hole size, water in cavity, and ice bypass.

Hole Size Adjustment. Since no sample calculations were available to assess the effect of hole size, Expert A used an analogy to the effect of ice depletion. In Reference A-1, the effect of ice depletion in the absence of a hydrogen burn lead to a pressure increase from 4.3 to 6.7 bar, or 2.4 bar. The larger the vessel hole size, the greater the intercompartmental flow rates, and the less time available for heat transfer to the ice. Therefore, this pressure rise can be taken as a limit for zero heat transfer. Expert A concluded that a median pressure increase of 1.0 bar could be added to any dry case result to account for a large hole size. The upper bound could increase by 2.0 bar, and the lower bound would remain the same.

As an example, the median for Case 1a, with $f = 0.75$ and small vessel hole size, in example (a) would be increased from 4.5 bar to 5.5 bar, when adjusted for large hole size. The upper bound for Case 1a, $f = 1.0$ in example (b) would be increased from 7.0 bar to 9.0 bar, when the hole size adjustment is made.

Water in Cavity Adjustment. Expert A noted that the effect of coentrained water at Sequoyah from Reference A-1 was a pronounced reduction in pressure, but that another possible outcome of a wet cavity case would be a complete debris quench. Therefore, the lower bound final pressure resulted from a complete quench, adding 0.5 bar to the initial containment pressure, regardless of initial vessel pressure. The median and upper bound would scale between this value and the corresponding value for DCH given in a dry cavity case. The final pressure considering a wet cavity is thus:

Lower Bound:

$$P_{\text{wet}} = P_1 + 0.5 = 2.0 \text{ bar} \quad (14)$$

Median and Upper Bounds:

$$P_{wet} = 1/2 * (P_{dry} - (P_1 + 0.5)) + (P_1 + 0.5) \text{ bar,} \quad (15)$$

where P_{dry} is calculated for the dry case as described above, including the adjustment for hole size, if applicable. No uncertainty was ascribed to the factor of 1/2 because it was felt that it would be an unnecessary embellishment, considering the other uncertainties.

As an example, the median value for dry Case 1a (and 2a) with $f = 0.75$ and a small vessel failure [example (a)], is 4.5 bar. The corresponding median for the wet cavity Case 1 (and 2) is $1/2 * (4.5 - 2) + 2 = 3.25$ bar. The upper bound pressure for Case 1a with $f = 1.0$ in example (b) is 7.0 bar, and the corresponding wet cavity case upper bound is thus $1/2 * (7.0 - 2) + 2 = 4.5$ bar. The upper bound case for wet cavity Case 1, $f = 1.0$, large hole size is $1/2 * (9.0 - 2) + 2 = 5.5$ bar.

Ice Bypass Adjustment: Cases 1b and 2b

The sensible pressure rise ratio for Case 1b and 2b for ice bypass was determined for the median value and then adjusted for the distribution. For $f = 0.75$ and no ice, the final pressure from Reference A-1 is 6.7 bar without a hydrogen burn, so the pressure ratio for that case is $6.7/1.5 = 4.47 \approx 4.50$. This is taken as an upper bound ratio. The upper bound ratio with ice is $1.5 + (.666) * 0.75 * 1.25 = 2.12$, so the multiplier to translate from an upper bound with ice case to an upper bound without ice case is $4.50/2.12 = 2.1 \approx 2.0$. For the median, considering cases 6 (no ice) and 4 (ice) of Reference A-1 with $f = 0.75$, the ratio here is $6.7/4.3 = 1.56 \approx 1.5$. A lower bound multiplier must exceed 1.0, and is chosen to be 1.25. The adjustment of the ice bypass cases is made by multiplying the sensible portion of the base case by these factors:

$$(P_2/P_1)_{sensible} \Big|_{bypass} = (P_2/P_1)_{sensible} \Big|_{no\ bypass} * f_{bypass} \quad (16)$$

where

$$f_{bypass} = \begin{cases} 1.25 & \text{lower bound} \\ 1.5 & \text{median} \\ 2.0 & \text{upper bound} \end{cases}$$

This procedure leaves open the possibility that unrealistically large pressures may result. From Reference A-1, p. 77, a maximum pressure of 14.9 bars was predicted by a DHEAT2 calculation. Therefore, the product of the pressure ratio and the initial pressure of 1.5 atm is limited to this value:

$$P_2 = \min (14.9, P_1 * (P_2/P_1)_{sensible}) \quad (17)$$

The sensible heat multiplier is identical for both small and large vessel hole sizes, and thus, when there is ice bypass, the hole size adjustment is not utilized.

The hydrogen burn pressure rise ratio can approach the AICC value for whatever hydrogen concentration would be in containment. However, there is no guarantee of complete mixing and hence some hydrogen may not burn due to steam inerting or oxygen starvation in the lower compartment. Furthermore, determination of the burn pressure rise ratio is complicated by the fact that it is a function of both steam and hydrogen concentrations. A maximum ratio for complete combustion is near 3.0 in the presence of steam for reasonable H_2 and H_2O concentrations, and a minimum is near 1.5. Since there is inadequate information to determine the H_2 and H_2O concentrations in each compartment, and thus the proper burn pressure rise ratio, a flat distribution is assumed between 1.5 and 3.0 for complete combustion. An uncertainty factor must be applied to account for incomplete combustion, which would reduce this ratio. Since some hydrogen is expected to not burn due to steam inerting or oxygen vitration, this multiplier cannot approach 1.0. The combustion completeness multiplier f_{cc} is chosen to be evenly distributed between 0.5 and 0.8, and it is applied as follows:

$$(P_f/P_2)_{burn} = 1 + f_{cc} * [(P_f/P_2)_{burn} - 1]. \quad (18)$$

As in the cases with ice, the burn pressure rise ratio depends upon the fraction of core expelled, and is unity for $f < 0.2$, reaches its maximum for $f > 0.4$, and varies linearly between. The burn pressure ratios are thus given by:

Median:

$$(P_f/P_2)_{burn} = \begin{cases} 1.0, & f \leq 0.2 \\ 1.0 + f_{cc} * (1.25/0.2) * (f - 0.2), & 0.2 < f \leq 0.4 \\ 1.0 + f_{cc} * 1.25, & f > 0.4. \end{cases} \quad (19)$$

Lower Bound:

$$(P_f/P_2)_{burn} = \begin{cases} 1.0, & f \leq 0.2 \\ 1.0 + f_{cc} * (0.5/0.2) * (f - 0.2), & 0.2 < f \leq 0.4 \\ 1.0 + f_{cc} * 0.5, & f > 0.4. \end{cases} \quad (20)$$

Upper Bound:

$$(P_f/P_2)_{burn} = \begin{cases} 1.0, & f \leq 0.2 \\ 1.0 + f_{cc} * (2.0/0.2) * (f - 0.2), & 0.2 < f \leq 0.4 \\ 1.0 + f_{cc} * 2.0, & f > 0.4. \end{cases} \quad (21)$$

Reviewing equations (19) through (21), the maximum value of this multiplier would be 3.0 for complete combustion but f_{cc} is limited to 0.8, so the maximum multiplier is 2.5. The median multiplier with $f_{cc} = 1.0$ would be 2.25, but with the median $f_{cc} = 0.65$, the value becomes 1.81. The hydrogen factor is not adjusted for vessel failure size.

As an example, the median for $f = 0.75$ with no ice is constructed by taking the sensible multiplier with ice, 2.0, and applying the median $f_{bypass} = 1.5$ to yield 3.0. As a check, $3.0 * 1.5 = 4.5$ is less than 14.9. The burn multiplier is taken with the median $f_{cc} = 0.65$ to yield 1.81. The final

pressure is $1.5 * 3.0 * 1.81 = 8.1$ bar. For an upper bound, considering $f = 1.0$, the sensible multiplier is 2.33 (with ice) $* 2.0$ (f_{bypass}) $= 4.66$, and the maximum burn multiplier is 2.6 , so the final pressure is $1.5 * 4.66 * 2.6 = 18.17$ bar.

Ice Bypass Adjustment: Case 3b

For Case 3b, the burn pressure ratio for cases 1b and 2b are computed. Then a "pressure adjustment" to the sensible portion is made as was done earlier, in adjusting from high RPV pressure to intermediate pressure:

$$(P_2/P_1)_{3b} - 1 = [(P_2/P_1)_{1b,2b} - 1] * g$$

where $.5 < g < 1$, and the distribution on g is uniform, and correlated with the distribution of P_2/P_1 .

Tabular Results - Cases 1, 2 and 3

Maximal uncertainty/entropy probability methods were used to obtain the distributions. The resulting values for ejected core fractions of 10%, 33%, 50%, 75%, and 100% are presented in Tables A-1 through A-10, for the cases given above. Tables A-1 to A-10 specify small/large vessel failure size parameter.

Table A-1
Base Cases 1a, 2a With Small Vessel Failure
(Final Containment Pressure, bar)

Percentile	$f=.1$	$f=.33$	$f=.5$	$f=.75$	$f=1.0$
1	2.33	2.68	3.28	3.52	3.75
5	2.33	2.74	3.35	3.60	3.84
25	2.34	3.04	3.69	4.00	4.30
50	2.35	3.42	4.13	4.50	4.88
75	2.36	4.07	4.95	5.46	5.96
95	2.37	4.60	5.62	6.22	6.83
99	2.38	4.70	5.75	6.38	7.00

Table A-2
Base Cases 1a, 2a With Large Vessel Failure
(Final Containment Pressure, bar)

<u>Percentile</u>	<u>f=.1</u>	<u>f=.33</u>	<u>f=.5</u>	<u>f=.75</u>	<u>f=1.0</u>
1	2.33	2.68	3.28	3.52	3.75
5	2.41	2.83	3.43	3.68	3.92
25	2.83	3.53	4.18	4.49	4.79
50	3.35	4.42	5.13	5.50	5.88
75	3.87	5.58	6.46	6.97	7.47
95	4.29	6.52	7.54	8.14	8.74
99	4.38	6.70	7.75	8.38	9.00

Table A-3
Base Case 3a With Small Vessel Failure
(Final Containment Pressure, bar)

<u>Percentile</u>	<u>f=.1</u>	<u>f=.33</u>	<u>f=.5</u>	<u>f=.75</u>	<u>f=1.0</u>
1	2.29	2.46	2.74	2.85	2.95
5	2.29	2.52	2.81	2.93	3.05
25	2.31	2.78	3.17	3.35	3.53
50	2.33	3.11	3.61	3.87	4.13
75	2.35	3.92	4.70	5.15	5.59
95	2.37	4.57	5.58	6.17	6.77
99	2.38	4.70	5.75	6.38	7.00

Table A-4
Base Case 3a With Large Vessel Failure
(Final Containment Pressure, bar)

<u>Percentile</u>	<u>f=.1</u>	<u>f=.33</u>	<u>f=.5</u>	<u>f=.75</u>	<u>f=1.0</u>
1	2.29	2.46	2.74	2.85	2.95
5	2.37	2.60	2.89	3.01	3.13
25	2.80	3.27	3.66	3.84	4.02
50	3.33	4.11	4.61	4.87	5.13
75	3.35	4.92	5.70	6.15	6.59
95	3.37	5.57	6.58	7.17	7.77
99	3.38	5.70	6.75	7.38	8.00

Table A-5
Base Cases 1 and 2 With Small Vessel Failure
(Final Containment Pressure, bar)

<u>Percentile</u>	<u>f=.1</u>	<u>f=.33</u>	<u>f=.5</u>	<u>f=.75</u>	<u>f=1.0</u>
1	2.00	2.00	2.00	2.00	2.00
5	2.01	2.06	2.09	2.10	2.12
25	2.09	2.35	2.52	2.61	2.70
50	2.18	2.71	3.06	3.25	3.44
75	2.18	3.04	3.48	3.73	3.98
95	2.19	3.30	3.81	4.11	4.41
99	2.19	3.35	3.88	4.19	4.50

Table A-6
Base Cases 1 and 2 With Large Vessel Failure
(Final Containment Pressure, bar)

<u>Percentile</u>	<u>f=.1</u>	<u>f=.33</u>	<u>f=.5</u>	<u>f=.75</u>	<u>f=1.0</u>
1	2.00	2.00	2.00	2.00	2.00
5	2.06	2.10	2.13	2.14	2.16
25	2.33	2.59	2.77	2.86	2.95
50	2.68	3.21	3.56	3.75	3.94
75	2.94	3.79	4.23	4.48	4.73
95	3.15	4.26	4.77	5.07	5.37
99	3.19	4.35	4.88	5.19	5.50

Table A-7
Base Cases 3 With Small Vessel Failure
(Final Containment Pressure, bar)

<u>Percentile</u>	<u>f=.1</u>	<u>f=.33</u>	<u>f=.5</u>	<u>f=.75</u>	<u>f=1.0</u>
1	2.00	2.00	2.00	2.00	2.00
5	2.01	2.05	2.07	2.08	2.09
25	2.08	2.27	2.39	2.46	2.52
50	2.16	2.55	2.80	2.93	3.06
75	2.18	2.96	3.35	3.57	3.80
95	2.19	3.29	3.79	4.09	4.38
99	2.19	3.35	3.88	4.19	4.50

Table A-8
Base Case 3 With Large Vessel Failure
(Final Containment Pressure, bar)

<u>Percentile</u>	<u>f=.1</u>	<u>f=.33</u>	<u>f=.5</u>	<u>f=.75</u>	<u>f=1.0</u>
1	2.00	2.00	2.00	2.00	2.00
5	2.05	2.09	2.11	2.12	2.13
25	2.32	2.52	2.64	2.70	2.77
50	2.66	3.05	3.30	3.43	3.56
75	2.68	3.46	3.85	4.07	4.30
95	2.69	3.79	4.29	4.59	4.88
99	2.69	3.85	4.38	4.69	5.00

Table A-9
Base Cases 1b and 2b With Large Vessel Failure
(Final Containment Pressure, bar)

<u>Percentile</u>	<u>f=.1</u>	<u>f=.33</u>	<u>f=.5</u>	<u>f=.75</u>	<u>f=1.0</u>
1	2.91	3.63	4.10	4.39	4.69
5	2.96	3.82	4.38	4.70	5.03
25	3.21	4.75	5.75	6.24	6.72
50	3.53	5.91	7.48	8.16	8.84
75	4.15	8.44	11.29	12.45	13.61
95	4.65	10.46	14.34	15.89	17.44
99	4.75	10.86	14.95	16.58	18.20

Table A-10
Base Case 3b With Small or Large Vessel Failure
(Final Containment Pressure, bar)

<u>Percentile</u>	<u>f=.1</u>	<u>f=.33</u>	<u>f=.5</u>	<u>f=.75</u>	<u>f=1.0</u>
1	2.20	2.69	2.99	3.13	3.28
5	2.27	2.88	3.26	3.43	3.61
25	2.60	3.82	4.60	4.93	5.25
50	3.02	5.01	6.29	6.80	7.31
75	3.90	8.00	10.71	11.79	12.86
95	4.61	10.39	14.24	15.78	17.31
99	4.75	10.86	14.95	16.58	18.20

Case 4, 4a, and 4b

As mentioned earlier, Expert A provided no distributions for Case 4. A point value, however, was provided. Expert A believed the pressure increment for Case 4 would be the same as Case 1 provided in Reference A-1, in which the blowdown pressure only is computed, resulting in a final containment pressure of 2.3 bar.

Hydrogen Production. Expert A provided a distribution for the fraction of potentially oxidizable metal in the ejected core that actually becomes oxidized during ejection for Cases 1, 2 and 3. The distribution ranges from 50 to 100% and is uniform. The process is limited only by steam starvation which affects the upper end of the distribution, but it was judged that this distribution would be adequate. For Case 4, on the other hand, there is negligible hydrogen produced in the core ejection (gravity pour) process.

Hydrogen Consumption. Most of the hydrogen produced in direct containment heating will be consumed during subsequent burns. For Sequoyah, no values were provided in Reference A-1. Although values were provided for Zion, the containments are too different to make any accurate inferences from those values. Expert A therefore provided a value of 75% hydrogen consumption.

Sources of Uncertainty

Expert A felt the main uncertainties arise in this assessment with respect to the mode of debris dispersal (film vs. particle). There is also uncertainty associated with the creation of hydrogen (steam availability, debris dispersal, etc.), and the degree of oxygen availability due to hydrogen burns before vessel breach.

Suggested Methods for Reducing Uncertainty

Expert A believes that the ice bypass cases should be run with CONTAIN using large trapping fractions in the lower compartment. This would provide a baseline for fully 1/3 of the cases, since no such calculations were available that include the effects of hydrogen burns.

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Expert B's Elicitation

Issue 5: Pressure Increment in the Sequoyah Containment at Vessel Breach

Description of Expert B's Rationale/Methodology

Expert B observed that there was less known about DCH than about the other causes of the pressure rise listed above. There have been four DCH experiments at Sandia using the Surtsey facility. The initial CONTAIN predictions matched the DCH-1 experiment fairly well, and matched the DCH-2, DCH-3, and DCH-4 tests poorly. A much better match to the later three DCH tests was obtained by changing the trapping parameter in CONTAIN from the value used for the DCH-1 test.

The effects of a wet cavity are hard to estimate; the water could make the pressure rise larger due to increased steam production, or the water could make the pressure rise smaller due to quenching.

The effects of a partially failed ice condenser are particularly hard to estimate since there are no experimental data and no analysis of this case.

The hot gases resulting from vessel breach at any pressure above a few hundred psia are expected result in ignition and complete combustion in any cell (volume) where a combustible mixture of hydrogen and oxygen is present. Some cells in the model do not burn because they have no oxygen available. Expert B concluded that detonations were unlikely, but credible, at Sequoyah.

At Sequoyah, when hydrogen ignition occurs before vessel breach, much of the hydrogen that was generated in-vessel is consumed. Ignition occurs before vessel breach when igniters are operating, and with an estimated frequency without the operation of igniters (addressed by containment loads experts in Issue 2). Expert B felt it was necessary to create an additional case-defining parameter to establish the containment hydrogen inventory at the time of vessel breach. Thus, the level of pre-existing hydrogen was added as an additional parameter to consider in the subcase definition.

Expert B considered Case 1 (2500 psia) and Case 2 (2000 psia) together as he thought there would be no appreciable differences between them. Factors other than the amount of pre-existing hydrogen, in-vessel zirconium oxidation, vessel hole size, and the fraction of mass ejected were accounted for by broadening the uncertainty bounds. In the course of this analysis, Expert B concluded that the pressure rise was fairly insensitive to the amount of in-vessel zirconium oxidation. Expert B provided pressure rises for sixteen subcases for each of the cases defined above. These subcases are defined by a four-letter code:

<u>Position</u>	<u>Description</u>	<u>Letter</u>	<u>Word</u>	<u>Nominal</u>	<u>Range</u>
First	Pre-Existing Hydrogen	Q	High	85% *	50 to 100%
		q	Low	25% *	0 to 50%
Second	In-Vessel Zr Oxidation	O	High	60%	40 to 80%
		o	Low	25%	10 to 40%
Third	Vessel Hole Size	H	Large	2 m ²	> 0.5 m ²
		h	Small	0.1 m ²	< 0.5 m ²
Fourth	Core Fraction Ejected	C	Large	75%	> 50%
		c	Small	33%	< 50%

*The level of pre-existing hydrogen refers to the percentage of hydrogen released in-vessel that still remains in containment at the time of vessel breach

Expert B denoted the Sequoyah cases with upper and lower case letter "Q". Thus, Case Q3b-OHc is Case 3b as defined above, with a high level of pre-existing hydrogen in containment, high oxidation of zirconium in-vessel, a large hole size, and a small fraction of the core ejected. Case q3b-OHc is identical to Q3b-OHc, except there is a low level of pre-existing hydrogen in containment.

Expert B approached the problem by using the available CONTAIN, MAAP, and Surtsey results to carefully assess pressure rise distributions for six base cases. Using a PC spreadsheet program, he then adjusted the six base cases to get values for all the other 138 subcases required.

The extremes of his ranges for the base cases were based on energy balance calculations which are relatively straightforward. The best estimate is based on code results, primarily CONTAIN results,^{B-1} and some subsequent calculations.^{B-2,B-3} Expert B spent most of his time on the base cases trying to get the center of his distributions correct, since that is where the bulk of the probability lies. Not as much time was spent with the low pressure rise end of the curves since the pressure rises in this region will not fail the containment. A fair amount of time was spent on the upper ends, however, even though containment failure is virtually assured for these pressure rises, because the base case is often reduced in calculating the subsidiary cases. As the base cases were picked to be about the most severe expected for the three RCS pressure levels, the base case is never increased enough in obtaining a derivative case that the low pressure rise end of the curve becomes important.

For Sequoyah, Expert B selected six base cases, denoted 1Q, 2Q, 3Q, 1q, 2q, and 3q. The full designation for each case and the reason it was selected are

<u>Base</u>	<u>Identifier</u>	<u>Reason for Selection</u>
1Q, 1q	Q1-oHC, q1-oHC	Full cavity likely for high pressure cases
2Q, 2q	Q3a-oHC, q3a-oHC	Dry cavity will probably give the highest Δp
3Q, 3q	Q4b-oHC, q4b-oHC	No ice will probably result in the highest Δp

Base Case 1Q: 2000 to 2500 psia in RCS, wet cavity, ice condenser functioning with ice remaining. The subcase is high pre-existing hydrogen in containment, low zirconium oxidation in-vessel, a large hole, and large fraction of core ejected. This is also denoted Case Q1-oHC. For his median value, Expert B started from Sequoyah Case 11 in Reference B-1. He reduced the fraction of the core participating in DCH from 75% because the Surtsey tests showed that not all the core participated.^{B-4 to B-7} Expert B also consulted other references,^{B-8, B-9} made further adjustments in the value from Reference B-1, and arrived at a median value of 5.5 bars.

The following is Expert B's complete pressure rise distribution for base case 1Q:

Cum. Prob.	0.01	0.05	0.25	0.50	0.75	0.95	0.99
Δp (bars)	1.0	2.0	4.0	5.5	8.0	13.5	15.0

For his base Case 1Q, Expert B obtained a range from 1 to 15 bars with the median at 5.5 bars. Note that these are pressure rises, not total resultant pressure as reported in Reference B-1. Specific reasoning, with detailed references, are available for each value given above in the notes of Expert B, which are too voluminous to be included here.

Expert B chose his upper bound (99% probability) to be somewhat above the largest pressure rise, 13.5 bars (the 95% value) for which there was a corresponding code result. For the lower bound (1% probability), he assumed that we had all seriously misunderstood the basic nature of melt ejection at high pressure and that the ejected material would all be quenched by the water in the cavity and the ice condenser. The resulting pressure rise is only 1 bar. For the 75% probability value, Expert B compared Surry cases 17 and 7 in Reference B-1. Assuming the 1 bar reduction^{*} is in error, he added 3.5 bars to his median value to get a Δp of 8.0 bars. For the 25% probability value, Expert B assumed that all the water was ejected from the cavity in the beginning by a steam explosion.

Base Case 1q: The case description is identical to base Case 1Q, except that there is a low level of pre-existing hydrogen in containment. This is also denoted Case q1-oHC. Considerable evidence in Reference B-6 suggests that cases "q" and "Q" are indistinguishable for this range of vessel pressure at breach. For high vessel pressure, large amounts of hydrogen are generated ex-vessel at breach. The hydrogen is transported throughout

^{*}J. L. Tills, "An Update on Direct Containment Heating for Ice Condenser Plants," presentation to Containment Loads Panel, 1/17/88, Jack Tills and Associates, Albuquerque, NM, 1988.

containment due to the pressure driven nature of the event. If there is any pre-existing hydrogen, it contributes little to the overall pressure rise. The family of cases associated with the 1q cases, therefore, are identical to the 1q cases, and the pressure rise distribution for base case 1q is:

Cum. Prob.	0.01	0.05	0.25	0.50	0.75	0.95	0.99
Δp (bars)	1.0	2.0	4.0	5.5	8.0	13.5	15.0

Base Case 2Q: 500 to 1000 psia in RCS, cavity dry, and IC functioning with ice remaining. The subcase is high level of pre-existing hydrogen, low zirconium oxidation, large hole, and large fraction of core ejected. This is also denoted Case Q3a-oHC. In these intermediate pressure cases, a substantial portion of the pressure rise comes from burning the pre-existing hydrogen, so reducing the fraction of the core which participates in DCH does not reduce the pressure rise accordingly.

Expert B arrived at the following pressure rise distribution for base case 2Q:

Cum. Prob.	0.01	0.05	0.25	0.50	0.75	0.95	0.99
Δp (bars)	0.7	1.1	2.8	5.5	7.0	10.0	14.0

The upper bound is 1.0 bar less than the upper bound in base Case 1Q, and the median value is the same value as the median in base Case 1Q. The median value for this base case is also based on the results of Sequoyah Case 11 in Reference B-1 even though the RCS pressure at vessel failure is much lower than in base Case 1Q. This reflects the relatively small number of CONTAIN calculations which were available for Sequoyah. The reasoning process away from CONTAIN Case 11 is quite different in base Case 2Q than in base Case 1Q. The reduced driving pressure in base Case 2Q is partially compensated by the fact that the cavity is dry in base Case 2Q, compared to the full cavity in base Case 1Q. After making several adjustments to account for hole size, fraction ejected, and other factors, Expert B arrived at 5.5 bars for his median pressure rise for base Case 2Q. For his 25% probability value (2.8 bars), Expert B assumed poor debris-steam contact as in some of the DCH experiments.

Expert B pointed out that the ice condenser is not effective in reducing the pressure rise when the steam concentration is low. High hydrogen-low steam gases are more likely in the high pressure scenarios than in the intermediate pressure case being considered here. There are several threshold effects which are difficult to account for satisfactorily.

Base Case 2q: The case description is identical to base Case 2Q, except that there is a low level of pre-existing hydrogen in containment. This is also denoted Case q3a-oHC. For intermediate vessel pressures at breach, the amount of pre-existing hydrogen becomes more important for the intermediate pressure cases than for the high pressure cases. Expert B noted that the weak steam driving force may result in less combustion of hydrogen generated ex-vessel, due to failure to transport the hydrogen from the lower compartment to other regions in containment. The values of pressure rise for base Case 2Q are therefore reduced for base Case 2q.

Expert B provided the following pressure rise distribution for base case 2q:

Cum. Prob.	0.01	0.05	0.25	0.50	0.75	0.95	0.99
Δp (bars)	0.5	0.75	1.5	4.5	6.5	9.0	13.0

Base Case 3Q: Less than 200 psia in RCS, dry cavity, and the ice condenser is bypassed or the ice is melted. The subcase is high level of pre-existing hydrogen, high zirconium oxidation, large hole, and large fraction of core ejected. This is also denoted Case Q4b-OHC. For this case, the important thing is the pre-existing hydrogen since DCH is negligible at these low RCS pressures. A large coherent burn can be expected, without mitigation due to ice. The middle and high end of the curve were based on various HECTR results (cases N.00, A.00, and B.00 in Reference B-10) since this is a straightforward hydrogen burn problem. The lower end assumes no ignition or incoherent burns due to steam inerting, and negligible pressure rise due to corium contact with the cement.

Expert B arrived at the following pressure rise distribution for base Case 3Q:

Cum. Prob.	0.01	0.05	0.25	0.50	0.75	0.95	0.99
Δp (bars)	0.1	0.5	4.6	7.5	11.7	13.0	14.0

Base Case 3q: The case description is identical to base Case 3Q, except that there is a low level of pre-existing hydrogen in containment. This is also denoted Case q4b-OHC. Expert C allowed some pre-existing hydrogen in this case (nominal value is 25% of the in-vessel hydrogen production), which would result in a global concentration of 3.3% in containment. This is below the ignition criterion. Burns were assumed only at the upper end of the distribution (above the 75% probability value), allowing for higher local concentrations of hydrogen, yet still weak incoherent burns. The pressure rises at the lower end of the distribution would be due to small amounts of steam being released at vessel failure.

Expert B provided the following pressure rise distribution for base case 3q:

Cum. Prob.	0.01	0.05	0.25	0.50	0.75	0.95	0.99
Δp (bars)	0.05	0.1	0.3	0.5	0.8	1.2	1.5

Expert B derived the pressure rise distributions for all the other cases by means of adjustments to the three base cases described above. These adjustments and the reasoning behind them are described in Expert B's notes which are not included here. As an example, in obtaining the small fraction of core ejected cases from the large fraction of core ejected cases, he reduced the median pressure rise by 0.5 bar since reducing the fraction of the core ejected in various CONTAIN runs showed such an effect.

Results of Expert B's Elicitation

Expert B provided a table giving the 1%, 5%, 25%, 50%, 75%, 95%, and 99% values for 144 cases and subcases. For listing here, only the 5%, 50% and 95% values are shown. Furthermore, Expert B concluded that the effects of some of the subcase parameters could not be distinguished in the presence of other uncertainties for certain cases. For the Q1 and q1 family of cases, the amount of pre-existing hydrogen is unimportant, as well as the amount of in-vessel zirconium oxidation. The effect of the amount of in-vessel zirconium oxidation could not be distinguished for the q3 cases. Thus the results for Q1-OHC and q1-OHC are the same as for Q1-oHC and q1-oHC, for example. This variable has therefore been eliminated for the Q1 and q1 cases, and only four subcases (HC, hC, Hc, and hc) are shown for each case in the following table. For most of the Q4 cases, Expert B concluded that only the amount of zirconium oxidation in vessel was important. For example, the results for Q4-OHC are the same as his pressure rises for Q4-OhC, Q4-OHc, and Q4-Ohc. Therefore, this variable has been eliminated for the Q4 case, and only two subcases (O and o) are shown. The pressure rises in the following tables are in bars.

Pressure Rise at VB for High
Pressure Cases

<u>Case</u>	<u>5%</u>	<u>50%</u>	<u>95%</u>
Q1-HC, q1-HC	2.0	5.5	13.5
Q1-Hc, q1-Hc	1.0	2.8	6.8
Q1-hC, q1-hC	1.6	4.4	10.8
Q1-hc, q1-hc	0.8	2.2	5.4
Q1a-HC, q1a-HC	2.0	5.0	13.5
Q1a-Hc, q1a-Hc	1.0	2.5	6.8
Q1a-hC, q1a-hC	1.6	4.0	10.8
Q1a-hc, q1a-hc	0.8	2.0	5.4
Q1b-HC, q1b-HC	2.0	9.4	14.9
Q1b-Hc, q1b-Hc	1.0	4.7	7.4
Q1b-hC, q1b-hC	1.6	7.5	11.9
Q1b-hc, q1b-hc	0.8	3.7	5.9

Pressure Rise at VB for High
Pressure Cases

<u>Case</u>	<u>5%</u>	<u>50%</u>	<u>95%</u>
Q3 -OHC	3.6	7.2	10.5
Q3 -OHc	1.8	3.6	5.3
Q3 -OhC	2.9	5.7	8.4
Q3 -Ohc	1.4	2.9	4.2
Q3 -oHC	1.1	6.1	10.0
Q3 -oHc	0.6	3.0	5.0
Q3 -ohC	0.9	4.8	8.0
Q3 -ohc	0.4	2.4	4.0
q3 -HC	0.8	5.0	9.0
q3 -Hc	0.4	2.5	4.5
q3 -hC	0.6	4.0	7.2
q3 -hc	0.3	2.0	3.6
Q3a-OHC	3.6	6.5	10.5
Q3a-OHc	1.8	3.3	5.3
Q3a-OhC	2.9	5.2	8.4
Q3a-Ohc	1.4	2.6	4.2
Q3a-oHC	1.1	5.5	10.0
Q3a-oHc	0.6	2.8	5.0
Q3a-ohC	0.9	4.4	8.0
Q3a-ohc	0.4	2.2	4.0
Q3b-OHC	3.6	9.8	13.7
Q3b-OHc	1.8	3.3	5.3
Q3b-OhC	2.9	7.8	10.9
Q3b-Ohc	1.4	3.9	5.5
Q3b-oHC	1.1	8.3	13.0
Q3b-oHc	0.6	4.1	6.5
Q3b-ohC	0.9	6.6	10.4
Q3b-ohc	0.4	3.3	5.2
q3a-HC	0.8	4.5	9.0
q3a-Hc	0.4	2.3	4.5
q3a-hC	0.6	3.6	7.2
q3a-hc	0.3	1.8	3.6
q3b-HC	0.8	6.8	11.7
q3b-Hc	0.4	3.4	5.9
q3b-hC	0.6	5.4	9.4
q3b-hc	0.3	2.7	4.7

Pressure Rise at VB for High
Pressure Cases

<u>Case</u>	<u>5%</u>	<u>50%</u>	<u>95%</u>
Q4-0	1.5	8.3	13.0
Q4-o	1.3	2.0	4.2
Q4a-0	0.5	6.0	9.1
Q4a-o	0.3	1.0	2.9
Q4b-0	0.5	7.5	13.0
Q4b-o	0.3	1.2	4.2
q4-OHC	0.6	2.3	3.2
q4-OHc	0.6	1.8	2.7
q4-Ohc	0.6	1.8	2.7
q4-Ohc	0.6	1.3	2.2
q4-oHC	0.6	2.8	3.7
q4-oHc	0.6	2.3	3.2
q4-ohc	0.6	2.3	3.2
q4-ohc	0.6	1.8	2.7
q4a-0	0.1	0.3	1.0
q4a-o	0.1	0.3	1.0
q4b-0	0.1	0.5	1.2
q4b-o	0.1	0.5	1.2

Sources of Uncertainty

Expert 8 emphasized that there were many uncertainties in estimating containment loads, especially containment loads at vessel breach. Self-heating of the molten material as it travels from the vessel throughout containment is not accounted for in the lumped-parameter codes. This phenomenon is not captured in the Brookhaven experiments. Entrainment and Weber break-up are not mechanistically treated in the detailed codes. A zirconium oxide crust on the ejected droplets may cause them to behave like solid particles rather than liquid particles. Internal gas generation may fragment the droplets, thus affecting the particle size distribution.

Nitrogen chemistry is not included in any of the models. If nitrogen combines with the metal oxides in the droplet, the flow of nitrogen into the droplet may cause fragmentation if the nitrogen is subsequently released. The interactions of corium droplets with surfaces are not well understood; while it is known that molten corium does not wet concrete surfaces, and concrete spalls when covered with enough molten corium, exactly how the corium droplets will interact with concrete surfaces in a DCH event is unknown. The DCH experiments have shown that there is

considerable variability in trapping rates. Finally, the flow paths in the containment may change during the event as a result of the event itself. Expert B also pointed out that some facets of the pressure rise at vessel breach are nonlinear. For example, in a DCH event at Sequoyah, the pressure rise does not fall as the fraction of the core participating falls because much of the pressure rise is due to hydrogen combustion.

Two additional uncertainties apply to Sequoyah. The first is the possibility of a detonation at vessel breach, which is enhanced due to the high temperature gas conditions. As Expert B felt he had no way to approach the probability or results of a detonation at this time, he could not make explicit allowances for it. It is his opinion that the breadth of his distribution accounts for the possibility of detonation at least in part. The ice condenser itself introduces several uncertainties. In addition to the possibilities of channeling and partial ice depletion, the interaction of DCH with the ice condenser is very poorly understood.

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- B-2. D. C. Williams, "CONTAIN DCH Calculations for PWR's," Viewgraphs for NUREG/CR-1150 Containment Loads Panel (documented in Reference 3), December 17, 1987
- B-3. D. C. Williams et al., "Integrated Phenomenological Analysis of Containment Response to Severe Core Damage Accidents," Progress in Nuclear Energy, 19, 69, 1987.
- B-4. M. Pilch and W. W. Tarbell, "Preliminary Calculations on Direct Heating of a Containment Atmosphere by Airborne Debris," NUREG/CR-4455, SAND85-2439, Sandia National Laboratories, July 1986.
- B-5. W. Tarbell et al., "Results From the DCH-1 Experiment," NUREG/CR-4871, SAND86-2483, Sandia National Laboratories, June 1987.
- B-6. M. Pilch and W. W. Tarbell, "High Pressure Ejection of Melt from a Reactor Pressure Vessel: The Discharge Phase," NUREG/CR-4383, SAND85-0012, Sandia National Laboratories, September 1985.
- B-7. W. W. Tarbell et al., "Pressurized Melt Ejection into Scaled Reactor Cavities," NUREG/CR-4512, SAND86-0153, Sandia National Laboratories, October 1986.
- B-8. F. Haskin et al., "HECTR Results for Ice Condenser Containment Standard Problem," in Proceedings of the Second Containment Integrity Workshop, Crystal City, VA, NUREG/CP-0056, SAND84-1514, August 1984.
- B-9. Sequoyah Nuclear Plant Integrated Containment Analysis IDCOR Task 23.1," IDCOR Technical Report 23.1, Tennessee Valley Authority, Nuclear Engineering Branch, July 1984..
- B-10. A. L. Camp et al., "MARCH-HECTR Analysis of Selected Accidents in Ice Condenser Containments," Sandia National Laboratories, NUREG/CR-3912, SAND83-0501, 1983.

Expert C's Elicitation

Issue 5: Pressure Increment in the Sequoyah Containment at Vessel Breach

Description of Expert C's Rationale

Expert C consulted References C-1 through C-9 and provided a narrative description of the events he considered most likely to occur during pressurized melt ejection, based on experiments and calculations. When melt first enters the cavity, it spreads onto all the walls. The following gas entrains the liquid from the cavity. The flow would "dead end" at the seal table, then turn. The Expert does not believe that the melt will freeze on the walls. Approximately 80% of the melt will exit the cavity as droplets. The gas velocity will be several hundred m/s, and the droplet diameters must be in the range of tenths of millimeters. The droplets contain unreacted metallics, and zirconium would react in a fraction of a second. Therefore, if the droplets can be kept suspended for about one second, 100% zirconium reaction could occur, provided the atmosphere was not steam starved. The expert does not believe that the reaction will be turned off by low temperature. The chemical reactions will be very efficient and complete; all of the zirconium and 50% of the iron will be reacted, and all pre-existing hydrogen will be burned.

The gas has to make two 90° turns into the ice condenser, and droplets will be trapped before entering the ice condenser. Only steam and hydrogen will be transported through the ice condenser. High temperature hydrogen will exit the top of the ice condenser, and there will be a burn in the upper compartment, and the amount of hydrogen available is significant.

The Expert based his "best estimates" on CONTAIN calculations and on scaled experiments of the very similar Watts Bar containment. The case for RCS pressure 500 to 1000 psia was taken as a base, and the cumulative distribution function (CDF) for that case was perturbed for other cases. Cavity water could either enhance or reduce the pressure. The median was kept the same for wet cavity cases, but the distribution was stretched at both ends. On the low side, an overabundance of water might reduce pressure by two bars. On the high side, calculations indicate the possibility of increasing pressure by one bar.

He based the high side of his distributions on getting a steam blowdown which optimized entrainment, and on burning the remaining iron. On the low side, he considered phenomena which might reduce pressure; larger drop diameter, or faster trapping. Calculations had indicated that pressure might be reduced by one bar for larger drops and one bar for better trapping. He thus considered that the base case pressure could be reduced by three bars for the 5th percentile.

Dependence on extent of zirconium oxidation, vessel breach area, and fraction of melt ejected was also to be considered. CONTAIN calculations had indicated that there was little dependence on previous zirconium oxidation. The reason for low dependence on previous zirconium oxidation

might be oxidation starvation or steam starvation in the cavity; he considers the latter to be doubtful. The effect of greater hole area is to give higher pressure across the entire band, because the gas would exit with higher velocity. The effect of fraction of core ejected was handled by scaling the base case ratio of final to initial pressure. If the fraction of melt is reduced from 75 to 25%, this would reduce pressure increment by a factor of 0.6.

Results of Expert C's Elicitation

Tentatively, the Expert suggested applying the results below for Cases 3 and 3A to Cases 1, 1A, 2, and 2A.

Table C-1
Case 3A (Pressure Increment, Bars)

Melt Mass Ejected	Break Area m ²	Fractiles				
		.05	.25	.50	.75	.95
75%	0.1	3.0	4.0	5.0	6.5	8.0
	2.0	4.0	5.0	6.0	7.5	9.0
25%	0.1	2.0	2.5	3.0	4.0	5.0
	2.0	2.5	3.0	3.5	4.5	5.5

Table C-2
Case 3 (Pressure Increment, Bars)

Melt Mass Ejected	Break Area m ²	Fractiles				
		.05	.25	.50	.75	.95
75%	0.1	1.0	2.0	5.0	7.5	9.0
	2.0	2.0	3.0	6.0	8.5	10.0
25%	0.1	1.0	1.5	3.0	4.5	5.5
	2.0	1.5	2.0	3.5	5.0	6.0

Sources of Uncertainty

A major source of uncertainty is the effect of cavity water. This could either increase or decrease the pressure increment. Other sources of uncertainty are the effects of drop diameter, the extent of iron oxidation, and the efficiency of trapping.

As shown in Tables C-1 and C-2, uncertainty in the initial conditions also leads to a large uncertainty in the results. The mass ejected and character of the blowdown could lead to large differences in the pressure increment.

REFERENCES

- C-1. D. C. Williams et al., "Containment Loads Due to Direct Containment Heating and Associated Hydrogen Behavior: Analysis and Calculations with the CONTAIN Code," NUREG/CR-4896, SAND87-0633, Sandia National Laboratories, May 1987.
- C-2. Electric Power Research Institute, "Hydrodynamics and Heat Transfer Aspects of Corium-Water Reactions," EPRI NP-5127, Electric Power Research Institute, 1987.
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- C-4. M. Pilch and W. W. Tarbell, "High Pressure Ejection of Melt from a Reactor Pressure Vessel: The Discharge Phase," NUREG/CR-4383, SAND85-0012, Sandia National Laboratories, September 1985.
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- C-7. L. C. Pong et al., "Application of a Direct Heating Model to the Sandia Surtsey Test," ANS Transactions, 53: 558-559, (1986).
- C-8. T. Ginsberg and N. Tutu, "A Direct-Heating of Containment Vessel Interaction Code (DHCVIC) and Predictions of SNL Surtsey Test DCH-1," ANS Transactions, 53: 559-561, (1986).
- C-9. D. E. Mitchell and N. A. Evans, "Steam Explosion Experiments at Intermediate Scale: FITSB Series," NUREG/CR-3983, SAND83-1057, Sandia National Laboratories, February 1986.

5.6 Containment Loads Issue 6: Loads at Vessel Breach--Surry

Summary of Expert Panel's Assessment of Issue 6: Loads at Vessel Breach--Surry

Experts consulted: Ken Bergeron, Sandia National Laboratories; Ted Ginsberg, Brookhaven National Laboratory; James Metcalf, Stone & Webster; Fred Torri, Pickard Lowe & Garrick.

Issue Description

What distributions characterize the uncertainty in the pressure rise in containment at vessel breach for Surry. This pressure rise may result from one or more of the following events:

1. Blowdown of the reactor coolant system (RCS);
2. Ex-vessel molten core-coolant interactions (MCCI);
3. Hydrogen combustion;
4. Direct containment heating (DCH).

RCS blowdown and DCH cause significant loads to the containment only if the RCS pressure is ten to twenty atmospheres or more above that of the containment at vessel breach.

The initial presentation of this issue delineated four RCS pressure ranges for consideration. The four pressure ranges were later reduced to three, and the case structure for Surry was redefined as follows:

<u>Case</u>	<u>RCS Pressure (psia)</u>	<u>Cavity Water</u>	<u>Sprays Operating</u>
1	2000 to 2500	Full	Yes
1a	2000 to 2500	Half	Yes
1b	2000 to 2500	Dry	No
1c	2000 to 2500	Full	No
3	500 to 1000	Full	Yes
3a	500 to 1000	Half	Yes
3b	500 to 1000	Dry	No
4	15 to 200	Half	Yes

The panel decided to consider the following variations on these basic cases:

Zirconium oxidation: high (60%) and low (25%),
Melt fraction ejected: high (75%) and low (33%), and
Initial hole size: large (2 m²) and small (0.1 m²)

As a result, there were eight subcases for each of the eight cases listed above.

Summary of Experts' Rationale/Methodology

Expert A calculated three base case distributions for the pressure rise at vessel breach at Surry. He then derived the distributions for rest of the cases presented in the issue description by adjusting the three base case distributions. The base cases chosen were expected to represent the most severe pressure rises for the three different RCS pressure levels analyzed. The three base cases chosen by Expert A are:

<u>Base Case</u>	<u>RCS Pressure(psia)</u>	<u>Cavity Water</u>	<u>Sprays Operating</u>
1b	2000 to 2500	Dry	No
3b	500 to 1000	Dry	No
4	15 to 200	Half	Yes

The Expert also considered the differences in pressure rise due to the amount of in-vessel zirconium oxidation, the RCS hole size, and the fraction of mass ejected. For the base case calculations, the Expert chose a specific set of these additional parameters to consider.

Expert A approached the problem by using the available CONTAIN, MAAP, and Surtsey results to carefully assess pressure rise distributions for three base cases. Using a PC spreadsheet program, he then adjusted these base cases to get values for the other 61 subcases required to quantify the requested cases.

The extremes of his ranges for the base cases were based on energy balance calculations. The best estimates were based on code results, primarily CONTAIN results as reported in NUREG/CR-4896,^{A-1} and some subsequent calculations.^{A-2 to A-6}

Expert B based his "best estimates" on CONTAIN calculations and on scaled experiments. The case for the 500 to 1000 psia pressure range was taken as a base, and the CDF for that case was perturbed for other cases. Cavity water could either enhance or reduce the pressure. The median was kept the same for wet cavity cases, but the distribution was stretched at both ends. On the low side, an overabundance of water might reduce pressure by two bars. On the high side, calculations indicate the possibility of increasing pressure by one bar.

He based the high side of his distributions on a one-cell, adiabatic equilibrium code written by the expert for the Zion and Surry. While calculating the low side of the distribution, he considered phenomena that might reduce pressure: larger drop diameter, or faster trapping.

Also considered were dependence on extent of zirconium oxidation, vessel breach area, and the fraction of melt ejected. CONTAIN calculations have indicated that there is little dependence on previous zirconium oxidation probably due to oxidation starvation in the cavity. The effect of greater hole area is to give higher pressure across the entire distribution,

because the gas would exit with higher velocity. The effect of fraction of core ejected was handled by scaling the base case ratio of final to initial pressure.

The Expert described what he thought would occur during pressurized melt ejection, based on experiments and calculations: when melt first enters the cavity, it spreads onto all the walls. The following gas entrains the liquid from the cavity. The Expert does not believe that the melt will freeze on the walls. Approximately 80% of the melt will exit the cavity as droplets. The gas velocity will be several hundred m/s, and the droplet diameters must be in the range of tenths of millimeters. The droplets contain unreacted metallics, and zirconium would react in a fraction of a second. Therefore, if the droplets can be kept suspended for about 1 s, 100% zirconium reaction could occur, provided the atmosphere was not steam-starved. The Expert does not believe that the reaction will be turned off by low temperature. The chemical reactions will be very efficient and complete; all of the zirconium and 50% of the iron will be reacted, and all pre-existing hydrogen will be burned.

Expert G referenced HMC calculations by Corradini (HMC is a computer program which combines the HECTR, MEDICE-M1, and CORCON-MOD2 codes into an integrated package), Sandia CONTAIN calculations, and MAAP calculations. He tabulated the cases described in the issue description and applied available code calculations that he could to each case. In many cases, modifications were made by the Expert to account for differences between the initial conditions in the code calculations and the case under consideration.

The Expert used the HMC calculations for several cases in which there was water in the cavity. The Expert considered the highest pressure calculated by Corradini to be the upper bound. He considered the pressure increment without direct heating to be the lower bound.

The Expert used CONTAIN and MAAP results in cases in which the cavity was dry. CONTAIN calculations for unconditional hydrogen burn and default burn were averaged and used for the upper part of the distribution. The MAAP results were used for the lower part of the distribution. The median was selected between the two sets of calculations.

Although he believed the CONTAIN calculations to be consistently above the median, he considered the results credible. He used the CONTAIN sensitivity calculations to estimate the effects of changes in initial conditions, and applied these to the requested case structure.

Expert D used CONTAIN results as the basis for his analysis because CONTAIN is currently the only code which has a DCH model. Expert D defined his base case as follows: he started from the 18-node Surry model with unconditional hydrogen burn (DCHB). He then made several adjustments to this value considering alternate particle sizes, an alternate trapping model and the effect of the thin steel in the containment on peak pressure. This case applies to the subcase with the large fraction of melt ejected (75%) and the small initial hole. Expert D concluded that the effects of codispersed water should not be included and that the fraction of the zirconium

oxidized in-vessel was not particularly important (CONTAIN runs in which the in-vessel oxidation was varied showed small differences in pressure rise). He also concluded that detonations would not occur.

For the small hole cases, Expert D adjusted the CONTAIN pressures upward somewhat since there is the possibility that more than one penetration may fail at or about the same time.

The Expert calculated that the peak pressure with sprays operating is expected to be about 1.5 to 2.5 bars lower than the equivalent case without the sprays operating.

There is considerable dependence on the particle size in the upward direction. If the particle size assumed in the CONTAIN runs (1.0 mm) is increased, the pressure rise will decrease because the material in the center of the particle will not have reacted before the particle is quenched. If the particle size is decreased from that assumed in CONTAIN, there is a negligible effect since all the metal in the particle is reacting already.

CONTAIN assumes that the core debris distributed throughout the containment during the blowdown phase of the DCH process is homogeneous. Expert D expects the entrained material to be richer in oxides than a homogeneous mixture. Expert D also pointed out that, when DCH occurs, only a very small portion of the hydrogen pre-existing in the containment or produced during the HPME can be expected to remain unburned after the event is over.

Method of Aggregation

Expert D gave estimates only for the 5th, 50th, and 95th percentiles. To make Expert D's distributions more compatible with those of the other experts, his 5th and 95th percentile values were extrapolated linearly to the 1st and 99th percentiles. Expert D also did not give distributions for Case 4, the values for Case 4 were taken from the aggregated distribution for the other three experts. Only one expert had any differences whatsoever for high vs. low zirconium oxidation, and he had small differences only for cells having low pressures. Therefore, low and high zirconium oxidation levels have been combined. There are thus four subcase levels, corresponding to combinations of low and high fraction ejected with large and small hole areas.

The data were analyzed as a "block factorial" or "factorial repeated measures" experiment, that is, an experiment having more than one type of treatment, in which every combination of treatment levels is applied to each subject. The treatment types are considered to be "Cases", with eight levels, and "Subcases", with four levels. An analysis of variance (ANOVA) was carried out on the data for the 1st, 50th, and 99th percentiles of the experts' distributions. An ANOVA compares two independent estimates of the population variance: one computed from the treatment means (i.e., the "between treatments" variance) and the other as the "within treatments" variance. This is equivalent to comparing the variance in the dependent variable attributable to the treatments with the unexplained (residual) variance.

The differences between experts are indeed significant. For some percentiles more of the variance is attributable to the differences between experts than to the differences between cases, although the differences due to cases were also significant. There are no significant case x subcase interactions, indicating that the experts applied the subcase variations consistently to each case.

Contrasts of main effects for cases were tested. "Main effects" means are the means of the dependent variable (the pressure increment) averaged over all subcases and experts for each case. The differences between main effects means were tested by a least significant difference (LSD) test. The LSD is the smallest absolute value of the differences between two means which should be considered significant. In order to retain as many cases as necessary, the significance level for the LSD test was set quite high (20%). Even with this high value, the ANOVA showed that Cases 1, 1a, and 3b can be combined, as can Cases 1b, and 1c and Cases 3 and 3a.

In order to test the differences attributable to individual subcases, a simple main effects ANOVA was performed. This ANOVA compares the variance attributable to the subcases evaluated at each of the cases to the residual variance. At least for the 50th and 99th percentiles, subcases are significantly different for all cases. For Case 4, however, there is only a marginal significance at the 99th percentile. All subcases could thus be combined for Case 4, but not for any other cases.

There were originally 64 subcases, but the elimination of the distinction made on zirconium oxidation reduced the number to 32. When Cases 1, 1a, and 3b, and 1b and 1c, and 3 and 3a are combined and subcase distinctions are dropped for Case 4, there remain only 13 distinct subcases. These subcases are listed in Table 6-1. Each expert's data for Cases 1 and 1a, and 3b and for 1b and 1c and for 3 and 3a were averaged, as were subcases for Case 4.

Table 6-1
Characteristics of Combined Cases

<u>Case</u>	<u>RCS Pressure</u>	<u>Cavity</u>	<u>Vessel Hole Size</u>	<u>Core Fraction Ejected</u>
1	High ^{a,b}	Wet ^a	Large ^d	High ^e
2	High ^{a,b}	Wet ^a	Large	Low ^f
3	High ^{a,b}	Wet ^a	Small ^a	High
4	High ^{a,b}	Wet ^a	Small	Low
5	High	Dry	Large	High
6	High	Dry	Large	Low
7	High	Dry	Small	High
8	High	Dry	Small	Low
9	Intermediate ^a	Wet	Large	High
10	Intermediate	Wet	Large	Low
11	Intermediate	Wet	Small	High
12	Intermediate	Wet	Small	Low
13	Low ^h	Any	Any	Any

^aAlso applies to Intermediate and Dry.

^b2000 to 2500 psi

^c75%

^d2 m²

^e0.1 m²

^f33%

^g500 to 1000 psi

^h50 to 200 psi

Aggregated Results

Data were reduced by arithmetic averaging; for each pressure increment value, probabilities were determined for each expert by interpolation, and the probabilities were then averaged. Interpolation was then used on the averaged CDFs to find values for the 1st, 5th, 25th, 50th, 75th, 95th, and 99th percentiles. In view of the large differences between experts, it is unnecessary to use a finer subdivision of the CDF than this. Table 6-2 shows the results for the aggregated CDFs.

Table 6-2
Aggregate Results Pressure Rise at
Vessel Breach for Surry (bars)

Case	Hole Size	Amount Ejected	Fractile						
			0.01	0.05	0.25	0.50	0.75	0.95	0.99
1	Large	High	1.4	2.3	4.1	5.8	7.8	10.7	13.2
2	Large	Low	1.1	1.6	2.5	4.2	5.9	8.2	10.4
3	Small	High	1.0	1.9	3.6	5.2	6.7	9.6	11.7
4	Small	Low	0.8	1.4	2.4	3.5	4.9	6.8	8.8
5	Large	High	1.7	2.8	4.9	7.3	9.3	11.8	13.6
6	Large	Low	1.3	1.9	3.3	5.0	6.6	9.3	10.8
7	Small	High	1.2	2.2	4.3	6.0	7.7	10.0	11.7
8	Small	Low	1.0	1.7	2.6	3.8	5.7	7.5	9.1
9	Large	High	1.1	1.8	3.4	4.8	6.8	9.8	12.2
10	Large	Low	0.7	1.1	2.0	4.0	5.2	7.7	9.3
11	Small	High	0.9	1.6	3.2	4.5	5.8	9.4	11.7
12	Small	Low	0.6	1.1	1.9	3.0	4.4	6.8	8.6
13	Any	Any	0.2	0.4	0.7	1.0	1.5	3.1	5.0

For use in the user function of the Accident Progression Event Tree, the fraction of melt ejected was divided into three groups: 0 to 20%, 20 to 40%, and 40 to 60%. The reason for doing this is that the dividing point between high and low fraction ejected (50% ejected) used by the Loads Panel turns out to be very near the high end of the aggregate distribution given for the fraction of melt ejected by the In-Vessel Panel. If the high-low division given by the Loads Panel was used, over 80% of the cases would fall in the low category.

Since it was not possible to get the Containment Loads Panel to evaluate a new set of distributions, the data can be manipulated in the following way. For the 20 to 40% ejected group, the low-fraction-ejected results from the Loads Panel can be used directly since the nominal value used by the Loads experts was 33% ejected. For the 40 to 60% ejected group, the loads low-fraction-ejected and high-fraction-ejected can be averaged. The average of the nominal fractions ejected is 54%, which is reasonably close to the center of this group. For the 0 to 20% ejected group, the average of the low fraction and the Case 4 results (< 200 psia) can be used.

Table 6-3 gives the new description of the, now, 19 cases in terms of RCS pressure, amount of cavity water, whether the sprays are operating, the core fraction ejected, and the vessel hole size. Table 6-4 shows the aggregate results for the pressure rise at Surry (Table 6-2) expanded to three fraction-ejected groups by the method described above. Table 6-5 is Table 6-4 with the units converted from bars to psig for direct comparison with the results of the Structural Response Expert Panel.

Table 6-3
Characteristics of Combined Cases

<u>Case</u>	<u>RCS Pressure</u>	<u>Cavity</u>	<u>Vessel Hole Size</u>	<u>Core Fraction Ejected</u>
1	High ^{a,b}	Wet ^c	Large ^e	High ^d
2	High ^{a,b}	Wet ^c	Large	Medium ^a
3	High ^{a,b}	Wet ^c	Large ^f	Low
4	High ^{a,b}	Wet ^c	Small	High
5	High ^{a,b}	Dry	Small	Medium
6	High ^{a, b}	Dry	Small	Low
7	High	Dry	Large	High
8	High	Dry	Large	Medium
9	High	Dry	Large	Low
10	High	Dry	Small	High
11	High	Dry	Small	Medium
12	High	Dry	Small	Low
13	Intermediate ^h	Wet	Large	High
14	Intermediate	Wet	Large	Medium
15	Intermediate	Wet	Large	Low
16	Intermediate	Wet	Small	High
17	Intermediate	Wet	Small	Medium
18	Intermediate	Wet	Small	Low
19	Low ⁱ	Any	Any	Any

^aAlso applies to Intermediate and Dry.

^b2000 to 2500 psi

^c40 to 60%

^d2 m²

^e0.1 m²

^f0 to 20%

^g20 to 40%

^h500 to 1000 psi

ⁱ50 to 200 psi

Table 6-4
Aggregate Results Pressure Rise at
Vessel Breach for Surry (bars)

Case	Hole Size	Amount Ejected	Fractile						
			0.01	0.05	0.25	0.50	0.75	0.95	0.99
1	Large	40 to 60%	1.3	2.0	3.3	5.0	6.9	9.5	11.8
2	Large	20 to 40%	1.1	1.6	2.5	4.2	5.9	8.2	10.4
3	Large	0 to 20%	0.7	1.0	1.6	2.6	3.7	5.6	7.7
4	Small	40 to 60%	0.9	1.7	3.0	4.4	5.8	8.2	10.3
5	Small	20 to 40%	0.8	1.4	2.4	3.5	4.9	6.8	8.8
6	Small	0 to 20%	0.5	0.9	1.6	2.3	3.2	5.0	6.9
7	Large	40 to 60%	1.5	2.4	4.1	6.2	8.0	10.6	12.2
8	Large	20 to 40%	1.3	1.9	3.3	5.0	6.6	9.3	10.8
9	Large	0 to 20%	0.8	1.2	2.0	3.0	4.1	6.2	7.9
10	Small	40 to 60%	1.1	2.0	3.5	4.9	6.7	8.8	10.4
11	Small	20 to 40%	1.0	1.7	2.6	3.8	5.7	7.5	9.1
12	Small	0 to 20%	0.6	1.1	1.7	2.4	3.6	5.3	7.1
13	Large	40 to 60%	0.9	1.5	2.7	4.4	6.0	8.8	10.8
14	Large	20 to 40%	0.7	1.1	2.0	4.0	5.2	7.7	9.3
15	Large	0 to 20%	0.5	0.8	1.4	2.5	3.4	5.4	7.2
16	Small	40 to 60%	0.8	1.4	2.6	3.8	5.1	8.1	10.2
17	Small	20 to 40%	0.6	1.1	1.9	3.0	4.4	6.8	8.6
18	Small	0 to 20%	0.4	0.8	1.3	2.0	3.0	5.0	6.8
19	Any	Any	0.2	0.4	0.7	1.0	1.5	3.1	5.0

Table 6-5
Aggregate Results Pressure Rise at
Vessel Breach for Surry (psig)

Case	Hole Size	Amount Ejected	Fractile						
			0.01	0.05	0.25	0.50	0.75	0.95	0.99
1	Large	40 to 60%	18.1	28.3	47.9	72.5	99.4	137.1	171.1
2	Large	20 to 40%	16.0	23.2	36.3	60.9	85.6	118.9	150.8
3	Large	0 to 20%	9.4	14.5	23.2	37.7	53.7	81.9	111.7
4	Small	40 to 60%	13.1	23.9	43.5	63.1	84.1	118.9	148.7
5	Small	20 to 40%	11.6	20.3	34.8	50.8	71.1	98.6	127.6
6	Small	0 to 20%	7.3	13.1	22.5	32.6	46.4	71.8	100.1
7	Large	40 to 60%	21.8	34.1	59.5	89.2	115.3	153.0	176.9
8	Large	20 to 40%	18.9	27.6	47.9	72.5	95.7	134.9	156.6
9	Large	0 to 20%	10.9	16.7	29.0	43.5	58.7	89.9	114.6
10	Small	40 to 60%	16.0	28.3	50.0	71.1	97.2	126.9	150.8
11	Small	20 to 40%	14.5	24.7	37.7	55.1	82.7	108.8	132.0
12	Small	0 to 20%	8.7	15.2	23.9	34.8	52.2	76.9	102.3
13	Large	40 to 60%	13.1	21.0	39.2	63.8	87.0	126.9	155.9
14	Large	20 to 40%	10.2	16.0	29.0	58.0	75.4	111.7	134.9
15	Large	0 to 20%	6.5	10.9	19.6	36.3	48.6	78.3	103.7
16	Small	40 to 60%	10.9	19.6	37.0	54.4	74.0	117.5	147.2
17	Small	20 to 40%	8.7	16.0	27.6	43.5	63.8	98.6	124.7
18	Small	0 to 20%	5.8	10.9	18.9	29.0	42.8	71.8	98.6
19	Any	Any	2.9	5.8	10.2	14.5	21.8	45.0	72.5

Individual Elicitations for Issue 6

Expert A's Elicitation

Issue 6: Pressure Rise at Vessel Breach for Surry

Description of Expert A's Rationale/Methodology

Expert A observed that there was less known about DCH than about the other causes of the pressure rise listed above. There have been four DCH experiments at Sandia using the Surtsey facility. The initial CONTAIN predictions matched the DCH-1 experiment fairly well, and matched the DCH-2, DCH-3, and DCH-4 tests fairly poorly. A much better match to the later three DCH tests was obtained by changing the trapping parameter in CONTAIN from the value used for the DCH-1 test.

The effects of a full cavity of water are hard to estimate; the water could make the pressure rise larger due to increased steam production, or the water could make the pressure rise smaller due to quenching. Expert A concluded that, for Surry, the median pressure rise for the full cavity case would be slightly higher than for the equivalent case with a dry cavity.

The hot gas resulting from vessel breach at any pressure above a few hundred psia will result in ignition if there is enough oxygen and hydrogen for combustion. The combustion should be complete. Expert A concluded that detonations were not likely at Surry. At the time of vessel breach, the pre-existing hydrogen would be cold and would deflagrate while the hydrogen plume from the vessel would be hot and would probably burn as a diffusion flame. At Surry, it is very unlikely that enough hydrogen could accumulate by the time of vessel breach to allow a global detonation. Expert A felt that local detonations could not be ruled out, however, and the possibility of detonations contributed to the spread in his distributions. The detonation mechanism is the failure of ignition or the diffusion flame for a few critical seconds as the hot gas flows out from the hole in the vessel. If this occurs, then detonable concentrations could exist in a limited volume.

The case structure listed above accounts for variations, in a coarse fashion, due to water in the cavity, sprays, and RCS pressure at vessel failure. The subcase structure accounts for differences due to the amount of in-vessel zirconium oxidation, the hole size, and the fraction of mass ejected. Other factors were accounted for by broadening the uncertainty bounds. In the course of this analysis, Expert A concluded that the pressure rise was fairly insensitive to the amount of in-vessel zirconium oxidation. The eight subcases are defined by a three-letter code:

<u>Position</u>	<u>Description</u>	<u>Letter</u>	<u>Word</u>	<u>Nominal</u>	<u>Range</u>
First	In-Vessel Zr Oxidation	O	High	60%	40 to 80%
		o	Low	25%	10 to 40%
Second	Vessel Hole Size	H	Large	2 m ²	> 0.5 m ²
		h	Small	0.1 m ²	< 0.5 m ²
Third	Core Fraction Ejected	C	Large	75%	> 50%
		c	Small	33%	< 50%

Expert A denoted his Surry cases with the letter "R". Thus, Case R3b-OHc is Case 3b as defined above, with high oxidation of zirconium in-vessel, a large hole size, and a small fraction of the core ejected.

Expert A approached the problem by using the available CONTAIN, MAAP, and Surtsey results to carefully assess pressure rise distributions for three base cases. Using a PC spreadsheet program, he then adjusted these base cases to get values for all the other 61 subcases required.

The extremes of his ranges for the base cases were based on energy balance calculations which are relatively straightforward. The best estimate is based on code results, primarily CONTAIN results as reported in Reference A-1, and some subsequent calculations.^{A-2 to A-4} Recent 18-cell CONTAIN results suggest, for example, that some of the earlier results may be too high by about 1.0 bar. Expert A spent most of his time on the base cases trying to get the center of his distributions correct, since that is where the bulk of the probability lies. He took very little time with the low pressure rise end of the curves since the pressure rises in this region will not fail the containment. He spent considerable time on the upper ends, however, even though containment failure is assured for these pressure rises, because the base case is often reduced in calculating the subsidiary cases. As the base cases were picked to be about the most severe expected for the three RCS pressure levels, the base case is never increased enough in obtaining a derivative case that the low pressure rise end of the curve becomes important.

For Surry, Expert A selected three bases cases, denoted 1R, 2R, and 3R. The full designation for each case and the reason it was selected are:

<u>Base</u>	<u>Identifier</u>	<u>Reason for Selection</u>
1R	R1b-oHC	Dry cavity more likely than full cavity at Surry
2R	R3b-oHC	Availability of results for comparison with 1R
3R	R4-oHC	Parallel parameter choice

Base Case 1R: 2000 to 2500 psia in RCS, cavity dry, and no sprays. The subcase is low zirconium oxidation in-vessel, a large hole, and large fraction of core ejected. For his median value, Expert A started from Surry Case 17 in Reference A-1, which has a pressure rise of 10.3 bars. He reduced this pressure by 0.8 bar because of the 18-cell results. He made another adjustment to account for the fraction of the core participating in DCH from 75% because the Surtsey tests showed that not all the core participated.^{A-5 to A-8} Expert A also relied on other recent CONTAIN calculations. After other adjustments for the zirconium oxidation fraction and trapping, Expert A arrived at a median value of 8.0 bars.

The following is Expert A's complete pressure rise distribution for base case 1R:

Cum. Prob.	0.01	0.05	0.25	0.50	0.75	0.95	0.99
Δp (bars)	1.0	2.0	5.0	8.0	10.0	13.0	15.0

The range is from 1 to 15 bars with the median at 8.0 bars. Note that these are pressure rises, not total resultant pressure as reported in Reference A-1. The median value is based on Cases 7, 17, and 26 in this work adjusted for the fraction ejected which participates in DCH, the fraction of zirconium oxidized in-vessel, the Surtsey experiments, the fraction of unoxidized metal in the ejecta, and the 18-cell results. More of these adjustments were negative than positive, so the pressure rise of 10.3 bars for Case 17 in Reference A-1 was, on the whole, adjusted downward more than two bars to get the midpoint value for this case.

Expert A chose his upper and lower bounds based on the report of the Containment Loads Working Group and several other calculations and analyses.^{A-9, A-10} The 25% and 75% pressure rises were selected to fit in between the median value and the bounds on the basis of the code calculations already referenced. Specific reasoning, with detailed references, are available for each value given above in the notes of Expert A, which are too voluminous to be included here.

Base Case 2R: 500 to 1000 psia in RCS, cavity dry, and no sprays. The subcase is low zirconium oxidation, large hole, and large fraction of core ejected. This is also denoted case R3b-oHC. The pressure rise distribution for this base case is primarily based on recent CONTAIN runs. For the median value, the adjustments made to the intermediate pressure result from this reference are much the same as those made for the median value in base case 1R. The median and upper bounds are somewhat lower than in base case 1R because of the lower pressure in the RCS at the time of vessel failure.

Expert A observed that, for Surry, the presence of water in the cavity increases the peak pressures when the RCS pressure is high before vessel breach but for intermediate pressures, as here, the presence of water decreases the resulting containment pressures. This is different from the behavior expected for Sequoyah, and the reason is that the cavity at Surry holds considerably less water than the cavity at Sequoyah. The presence of sprays and water in the cavity inhibit the pressure rise more

effectively for intermediate pressure in the RCS (base case 2R) than they do when there is full system pressure in the RCS at breach (base case 1R).

Expert A gave the following pressure rise distribution for base case 2R:

Cum. Prob.	0.01	0.05	0.25	0.50	0.75	0.95	0.99
Δp (bars)	0.8	2.0	4.5	6.7	8.7	11.0	14.0

The upper bound is 1.0 bar less than the upper bound in base case 1R, and the median value is 1.3 bars lower than the median in base case 1R.

Base Case 3R: less than 200 psia in RCS, full cavity, and sprays operating. The subcase is low zirconium oxidation, large hole, and large fraction of core ejected. This is also denoted case R4-oHC. The pressure rise in this case is due to phenomena other than DCH: steam spike, MCCI, and hydrogen combustion. DCH is negligible at these low RCS pressures. The distribution for pressure rise is largely derived from the various cases considered by the Containment Loads Working Group. The cases on which the middle and high end of the distribution rely on CONTAIN results^{A-3} while the low end reflects the pressure rise due to the steam spike alone.

Expert A arrived at the following pressure rise distribution for base case 3R:

Cum. Prob.	0.01	0.05	0.25	0.50	0.75	0.95	0.99
Δp (bars)	0.2	0.5	1.2	1.8	2.5	5.0	6.5

Expert A derived the pressure rise distributions for all the other cases by means of adjustments to the three base cases described above. These adjustments and the reasoning behind them are described in Expert A's notes which are not included here. As an example, in obtaining the small fraction of core ejected cases from the large fraction of core ejected cases, he reduced the median pressure rise since reducing the fraction of the core ejected in various CONTAIN runs showed such an effect.

Results of Expert A's Elicitation

Expert A provided a table giving the 1, 5, 25, 50, 75, 95, and 99% values for 64 cases and subcases. For listing here, only the 5, 50, and 95% values are shown. Furthermore, Expert A concluded that the effects of the amount of in-vessel zirconium oxidation could not be distinguished in the presence of other uncertainties for all cases except R4. (Case R4 is discussed below.) Thus his results for R1-oHC are the same as for R1-oHC, for example. Therefore, this variable has been eliminated and only four subcases (HC, hC, Hc, and hc) are shown for each case in the following table. The pressure rises in the following table are in bars.

<u>Case</u>	<u>5%</u>	<u>50%</u>	<u>95%</u>	<u>Case</u>	<u>5%</u>	<u>50%</u>	<u>95%</u>
R1 -HC	1.6	6.4	11.7	R1 -Hc	1.3	5.1	9.4
R1 -hC	1.1	4.5	9.4	R1 -hc	0.9	3.6	7.5
R1a-HC	2.0	8.0	13.0	R1a-Hc	1.6	6.4	10.4
R1a-hC	1.2	4.8	10.4	R1a-hc	1.0	3.8	8.3
R1b-HC	2.0	8.0	13.0	R1b-Hc	1.6	6.4	10.4
R1b-hC	1.4	5.6	10.4	R1b-hc	1.1	4.5	8.3
R1c-HC	2.2	8.8	13.0	R1c-Hc	1.8	7.0	10.4
R1c-hC	1.7	6.7	11.4	R1c-hc	1.3	5.4	9.2
R3 -HC	1.8	6.0	9.9	R3 -Hc	1.4	4.8	7.9
R3 -hC	1.5	5.1	9.4	R3 -hc	1.2	4.1	7.5
R3a-HC	2.0	6.7	11.0	R3a-Hc	1.6	5.4	8.8
R3a-hC	1.4	4.8	9.9	R3a-hc	1.2	3.9	7.9
R3b-HC	2.0	6.7	11.0	R3b-Hc	1.6	5.4	8.8
R3b-hC	1.7	5.7	10.4	R3b-hc	1.4	4.6	8.4
R4 -HC	0.4	1.6	4.5	R4 -Hc	0.2	0.9	2.5
R4 -hC	0.5	1.8	5.0	R4 -hc	0.2	0.8	2.2

For Case R4, there were slight differences in the pressure rise that depended on the amount of in-vessel zirconium oxidation for subcases hC, Hc, and hc. For subcases, the Hc and hc subcases, the 99% pressure rises are less than 3.5 bars and the 0-0 differences are less than 0.5 bars, so the differences are not worth preserving since the Surry containment will not be failed by pressure rises of this magnitude even if the lowest failure pressure given by the structural panel is used. For the hC subcase, the 99% values are 6.5 bars (for OhC) and 5.85 (for ohC). These values bring the load pressure into the lower portion of the range where failure of the containment is possible. The pressure rise distribution for subcase with the higher values (OhC) are listed above. If the elicitations of the other experts show strong dependencies on the amount of zirconium oxidation, the differences Expert A has given for case R4 will be utilized. In the table above, the differences between subcase HC and subcase hC are small, and the differences between subcase Hc and subcase hc are even smaller. A good argument can be made for combining these subcases for Case R4 so that only C and c subcases remain.

Sources of Uncertainty

Expert A emphasized that there were many uncertainties in estimating containment loads, especially containment loads at vessel breach. Self-heating of the molten material as it travels from the vessel throughout containment is not accounted for in the lumped-parameter codes. This phenomenon is not captured in the Brookhaven experiments. Entrainment and Weber break-up are not mechanistically treated in the detailed codes.

A zirconium oxide crust on the ejected droplets may cause them to behave like solid particles rather than liquid particles. Internal gas generation may fragment the droplets, thus affecting the particle size distribution.

Nitrogen chemistry is not included in any of the models. If nitrogen combines with the metal oxides in the droplet the flow of nitrogen into the droplet may cause fragmentation if the nitrogen is subsequently released. The interactions of corium droplets with surfaces are not well understood; while it is known that molten corium does not wet concrete surfaces, and concrete spalls when covered with enough molten corium, exactly how the corium droplets will interact with concrete surfaces in a DCH event is unknown. The DCH experiments have shown that there is considerable variability in trapping rates. Finally, the flow paths in the containment may change during the event as a result of the event itself.

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Expert B's Elicitation

Issue 6: Pressure Rise at Vessel Breach for Surry

Description of Expert B's Rationale/Methodology

The Expert provided a narrative description of the events he considered most likely to occur during pressurized melt ejection, based on experiments and calculations. When melt first enters the cavity, it spreads onto all the walls. The following gas entrains the liquid from the cavity. The flow would "dead end" at the seal table, then turn. The Expert does not believe that the melt will freeze on the walls. Approximately 80% of the melt will exit the cavity as droplets. The gas velocity will be several hundred m/s, and the droplet diameters must be in the range of tenths of millimeters. The droplets contain unreacted metallics, and zirconium would react in a fraction of a second. Therefore, if the droplets can be kept suspended for about one second, 100% zirconium reaction could occur, provided the atmosphere was not steam starved. The expert does not believe that the reaction will be turned off by low temperature. The chemical reactions will be very efficient and complete; all zirconium and 50% of the iron will be reacted, and all pre-existing hydrogen will be burned.

Expert B based his "best estimates" on CONTAIN calculations and on scaled experiments of the similar Zion containment. The case for vessel failure with the RCS at 500 to 1000 psia was taken as a base case, and the cumulative distribution function (CDF) for that case was modified for other cases. Cavity water could either enhance or reduce the pressure. The median was kept the same for wet cavity cases, but the distribution was stretched at both ends. On the low side, an overabundance of water might reduce pressure by two bars. On the high side, calculations indicate the possibility of increasing pressure by one bar.

He based the high side of his distributions on getting a steam blowdown which optimized entrainment, and on burning the remaining iron. On the low side, he considered phenomena which might reduce pressure; larger drop diameter, or faster trapping. Calculations had indicated that pressure might be reduced by one bar for larger drops and one bar for better trapping. He thus considered that the base case pressure could be reduced by three bars for the 5th percentile.

Dependence on extent of zirconium oxidation, vessel breach area, and fraction of melt ejected was also to be considered. CONTAIN calculations had indicated that there was little dependence on previous zirconium oxidation. The reason for low dependence on previous zirconium oxidation might be oxidation starvation or steam starvation in the cavity; he considers that latter to be doubtful. The effect of greater hole area is to give higher pressure across the entire band, because the gas would exit with higher velocity. The effect of fraction of core ejected was handled by scaling the base case ratio of final to initial pressure. If the fraction of melt is reduced from 75% to 25%, this would reduce pressure increment by a factor of 0.6.

Table B-1 contains the results of Expert B's elicitation. Expert B concluded that Cases 1 and 1C and Cases 3 and 3A were indistinguishable.

Table B-1
Loads at Vessel Breach at Surry for Expert B (bars)

Case	<u>Subcase</u>		<u>Fractile</u>						
	<u>Hole Size</u>	<u>Fraction Ejected</u>	<u>0.001</u>	<u>0.010</u>	<u>0.550</u>	<u>0.500</u>	<u>0.950</u>	<u>0.990</u>	<u>0.999</u>
1/1C	High	High	1.5	2.0	2.5	7.0	10.3	12.2	14.0
1/1C	High	Low	1.5	2.5	3.5	5.0	6.5	7.8	9.1
1/1C	Low	High	1.0	1.2	1.5	6.0	10.3	12.2	14.0
1/1C	Low	Low	1.5	2.0	2.5	4.0	5.5	6.8	9.1
1A	High	High	1.5	4.0	5.0	8.0	9.3	11.2	14.0
1A	High	Low	1.5	3.0	4.0	6.0	7.0	8.3	9.1
1A	Low	High	1.0	1.5	2.5	8.0	10.3	12.2	14.0
1A	Low	Low	1.5	2.5	3.5	5.0	6.5	7.8	9.1
1B	High	High	1.5	3.0	4.0	8.0	9.3	11.2	14.0
1B	High	Low	1.5	3.0	4.0	5.5	6.0	7.3	9.1
1B	Low	High	1.5	2.0	3.0	7.0	9.3	11.2	14.0
1B	Low	Low	1.5	2.0	3.0	4.5	6.0	7.3	9.1
3/3A	High	High	1.5	3.0	4.0	7.0	10.0	12.0	14.0
3/3A	High	Low	1.5	3.5	4.0	5.0	7.5	8.8	9.1
3/3A	Low	High	1.5	2.0	3.0	6.0	10.0	12.2	14.0
3/3A	Low	Low	1.5	1.8	2.0	4.0	7.0	8.3	9.1
3B	High	High	1.5	4.0	5.0	6.0	10.0	12.2	14.0
3B	High	Low	1.5	3.0	3.5	4.0	7.0	8.3	9.1
3B	Low	High	1.5	3.0	4.0	5.0	9.0	11.2	14.0
3B	Low	Low	1.5	2.0	2.5	3.0	6.0	7.3	9.1
4	High	High	0.2	0.5	1.0	1.3	1.8	2.0	2.5
4	High	Low	0.2	0.3	0.5	0.6	0.8	0.9	1.0
4	Low	High	0.2	0.5	1.0	1.3	1.8	2.9	2.5
4	Low	Low	0.2	0.3	0.5	0.6	0.8	0.9	1.0

Sources of Uncertainty

A major source of uncertainty is the effect of cavity water. This could either increase or decrease the pressure increment. Other sources of uncertainty are the effects of drop diameter, the extent of iron oxidation, and the efficiency of trapping.

As shown in Table B-1, uncertainty in the initial conditions also leads to a large uncertainty in the results. The mass ejected and character of the blowdown could lead to large differences in the pressure increment.

Expert C's Elicitation

Issue 6: Pressure Rise at Vessel Breach for Surry

Description of Expert C's Rationale/Methodology

Initial conditions for each case were subdivided by:

Fraction of zirconium oxidized before vessel breach--25% (low) and 60% (high); size of hole in vessel--0.1 m² (jet) and 2 m² (rip); fraction of melt ejected--25% (small) and 75% (major). For each case there are eight distinct sets of initial conditions. For example LJM would represent 25% zirconium oxidation, a 0.1 m² hole in the vessel, and 75% of the core promptly ejected.

As base cases, the HMC calculations by Corradini et al., and CONTAIN calculations by D. C. Williams were used. All the cases were tabulated; applicable calculations were then assigned to a specific case and set of initial conditions as shown in Table C-1. The calculations by Corradini were done for 100% melt ejection. The Expert reduced the pressure increment from the calculation by the ratio of melt ejected in the initial conditions; he was aware that the relation between pressure increment and fraction ejected was probably nonlinear, but had no other means of estimating the pressure increment corresponding to lower core fractions released. There were a large number of cases without a point estimate. Also, a large body of calculations performed by industry were unavailable.

Some of the cases were combined because of similarities, or because there is no information available for distinguishing them. For example, he believed that any water in the cavity would be dispersed almost immediately, and there was no way to distinguish between full and half cavities. Cases 1 and 1A were combined, as were Cases 3 and 3A.

In order to get a distribution, he considered the upper bound as the highest pressure calculated by Corradini. As a lower bound, the pressure increment without direct heating (i.e., a steam spike only) was used. For the high pressure cases, results calculated by Corradini were weighted according to how close the initial and boundary conditions approximated the desired case, and calculated a median value. For Cases 1B and 3B, he had access to both CONTAIN and MAPP calculations. CONTAIN calculations for unconditional hydrogen burn and default burn were averaged, and used for the upper part of the distribution. The MAPP results were consistently lower than CONTAIN results, and were used for the lower part of the distribution. The median was then selected between the two sets of calculations. A curve was then hand-fitted to the lower bound, median, and upper bound.

He believed the CONTAIN calculations to be consistently above the median, but that the reasons for the high values were rooted in the assumptions used. Given the assumptions, he considered the CONTAIN results to be credible. He was thus able to use the CONTAIN sensitivity calculations to estimate the effects of changes in initial conditions.

Table C-1
Calculations Applicable to Issue 6

<u>Case</u>	<u>Initial Conditions</u>	<u>Source</u>	<u>Maximum Pressure Increment (Bar)</u>	<u>Weight</u>
1	HRM	None		
1	HRS	None		
1	HJM	(C)* Case 2	3.6	0.05
		(C) Case 3	2.8	0.05
		(C) Case 5	3.15	0.10
		(C) Case 6	3.0	0.15
		(C) Case 8	6.3	0.05
		(C) Case 9	5.55	0.05
		(C) Case 10	3.65	0.25
		(C) Case 11	3.44	0.30
1	HJS	(C) Case 2	1.2	0.05
		(C) Case 3	0.94	0.05
		(C) Case 5	1.05	0.10
		(C) Case 6	1.0	0.15
		(C) Case 8	2.1	0.05
		(C) Case 9	1.85	0.05
		(C) Case 10	1.22	0.25
		(C) Case 11	1.15	0.30
1	LRM	None		
1	LRS	None		
1	LJM	None		
1	LJS	None		
1B	HRM	(W) Case 9	9.6	1.0
1B	HRS	(W) Case 8	5.1	1.0
1B	HJM	(W) Case 1	7.7	0.5
		(W) Case 3	6.6	0.5
1B	HJS	(W) Case 2	3.4	0.5
		(W) Case 4	2.0	0.5
1B	LRM	None		
1B	LRS	None		
1B	LJM	None		
1B	LJS	None		
1C	All	None		

Table C-1 (continued)

<u>Case</u>	<u>Initial Conditions</u>	<u>Source</u>	<u>Maximum Pressure Increment (Bar)</u>	<u>Weight</u>
3	All	None		
3B	HRM	(W) Case 10	6.9	1.0
3B	HRS	None		
3B	HJS	None		
3B	LRM	None		
3B	LRS	None		
3B	LJM	None		
3B	LJS	None		
4	HRM	None		
4	HRS	None		
4	HJM	(C) Case 2	1.15	0.33
		(C) Case 3	1.15	0.33
		(C) Case 4	0.32	0.33
4	HJS	(C) Case 2	0.38	0.33
		(C) Case 3	0.38	0.33
		(C) Case 4	0.11	0.33
4	All others	None		

(C) Corradini et al.
(W) D. G. Williams et al.

Table C-2 shows Expert C's distributions for those cases for which code results are available.

Table C-2
Distributions for Pressure Increment (bars)

<u>Case</u>	<u>Initial Conditions</u>	<u>Fractiles</u>				
		<u>.01</u>	<u>0.1</u>	<u>0.5</u>	<u>0.9</u>	<u>0.99</u>
1	HJM	2	3	4	5	6
1	HJS	1	1.5	2	2.5	3
1B	HJM	4	5	6	7	8
3B	HRM	4	5	6	7	8
3B	HJM	3	4.5	6	7.5	8.5
4	HJM	0.5	1	1.5	2	3

To aggregate the issues, the information missing from Expert C's elicitation was created from the data that Expert C provided. This aggregation was reviewed by the experts and the results appear in the following attachment.

Results of Expert C's Elicitation

Ratios are used to estimate the pressure rise distributions for each case and subcase for which there is no information in Table C-1. The ratio of "S" to "M" is estimated from cases 1 and 1B:

		<u>Fractile</u>				
Case	Subcases	.01	.10	.50	.90	.99
1	HJS:HJM	.5	.5	.5	.5	.5
1B	HRS:HRM	.444	.5	.5	.5	.5
1B	HJS:HJM	.375	.4	.417	.429	.438
	Mean	.440	.467	.472	.476	.479

Similarly, the ratio of "J" to "R" is estimated from cases 1B and 3B:

		<u>Fractile</u>				
Case	Subcases	.01	.10	.50	.90	.99
1B	HJM:HRM	.889	.833	.750	.700	.667
1B	HJS:HRS	.750	.667	.625	.600	.583
3B	HJM:HRM	.750	.900	1.000	1.071	1.062
	Mean	.796	.800	.792	.790	.771

The ratios of cases for which there are data are as follows:

		<u>Fractile</u>				
Cases		.01	.10	.50	.90	.99
1B:1		1.75	1.5	1.375	1.3	1.25
3B:1B		.75	.9	1.	1.067	1.067
4:1		.25	.333	.375	.5	.5
3B:1		1.5	1.5	1.5	1.5	1.42

There are no calculations or estimates for case 1C. If case 1C is equal to case 1, the following ratios between cases can be set up:

Case 3:Case 1 = Case 3B:Case 1/Case 3B:Case 3
Case 3:Case 1B = Case 3B:Case 1B/Case 3B:Case 3
Case 4:Case 1B = Case 4:Case 1/Case 1B:Case 1
Case 1C:Case 1B = Case 1:Case 1B
Case 3:Case 1C = Case 3:Case 1

In this manner, ratios were set up between all cases. The ratios for each fractile were calculated, so that the ratios between cases are quintuplets. Table C-3 shows the results of these calculations for all ratios between cases.

Table C-3
 Ratios for Loads at Vessel Breach at Surry for Expert C

Ratio of Case-to-Case		Fractile				
		.01	.10	.50	.90	.99
1	1	1.000	1.000	1.000	1.000	1.000
1B	1	1.750	1.500	1.375	1.300	1.250
1C	1	1.000	1.000	1.000	1.000	1.000
3	1	0.429	0.600	0.727	0.821	0.854
3B	1	0.750	0.900	1.000	1.067	1.067
4	1	0.250	0.333	0.375	0.500	0.500
1	1B	0.571	0.667	0.727	0.769	0.800
1B	1B	1.000	1.000	1.000	1.000	1.000
1C	1B	0.571	0.667	0.727	0.769	0.800
3	1B	0.245	0.400	0.529	0.631	0.683
3B	1B	0.750	0.900	1.000	1.067	1.067
4	1B	0.143	0.222	0.273	0.385	0.400
1	1C	1.000	1.000	1.000	1.000	1.000
1B	1C	1.750	1.500	1.375	1.300	1.250
1C	1C	1.000	1.000	1.000	1.000	1.000
3	1C	0.429	0.600	0.727	0.821	0.854
3B	1C	0.750	0.900	1.000	1.067	1.067
4	1C	0.250	0.333	0.375	0.500	0.500
1	3	2.333	1.667	1.375	1.218	1.172
1B	3	4.083	2.500	1.891	1.584	1.464
1C	3	2.333	1.667	1.375	1.218	1.172
3	3	1.000	1.000	1.000	1.000	1.000
3B	3	1.750	1.500	1.375	1.300	1.250
4	3	0.333	0.370	0.375	0.469	0.469
1	3B	1.333	1.111	1.000	0.937	0.937
1B	3B	1.333	1.111	1.000	0.937	0.937
1C	3B	1.333	1.111	1.000	0.937	0.937
3	3B	0.571	0.667	0.727	0.769	0.800
3B	3B	1.000	1.000	1.000	1.000	1.000

Table C-3 (continued)

Ratio of Case-to-Case		Fractile				
		.01	.10	.50	.90	.99
4	3B	0.333	0.370	0.375	0.469	0.469
1	4	4.000	3.003	2.667	2.000	2.000
1B	4	7.000	4.505	3.667	2.600	2.500
1C	4	4.000	3.003	2.667	2.000	2.000
3	4	3.000	2.703	2.667	2.134	2.134
3B	4	3.000	2.703	2.667	2.134	2.134
4	4	1.000	1.000	1.000	1.000	1.000

The next step to consider each of the cases and subcases for which there is no pressure rise distribution. If the case/subcase distribution is not available, first look through all subcases of the same case. If any distributions are available, calculate each fractile as the mean of the subcase ratios times the fractile value for the distributions that are available. If there are no distributions given within that case, calculate each fractile as the mean of the subcase ratios times the case ratios for all case/subcase combination (that is, for any case) for which distributions are available.

The advantage of this method is that the results are internally consistent. There is no differentiation between low and high zirconium oxidation as Expert C believed the effect of zirconium oxidation would be small. The results of Expert C are shown in Table C-4.

Table C-4
Loads at Vessel Breach at Surry

Case		Fractile				
		.01	.10	.50	.90	.99
1/1A	HRM	2.8	3.5	4.1	4.8	5.7
1/1A	HRS	1.3	1.6	1.9	2.3	2.8
1/1A	HJM	2.0	3.0	4.0	5.0	6.0
1/1A	HJS	1.0	1.5	2.0	2.5	3.0
1B	HRM	4.5	6.0	8.0	10.0	12.0
1B	HRS	2.0	3.0	4.0	5.0	6.0
1B	HJM	4.0	5.0	6.0	7.0	8.0
1B	HJS	1.5	2.0	2.5	3.0	3.5

Table C-4 (continued)

Case	Subcase	Fractile				
		.01	.10	.50	.90	.99
1C	HRM	3.2	3.9	4.8	5.6	6.8
1C	HRS	1.4	1.8	2.3	2.7	3.3
1C	HJM	2.4	3.6	4.8	6.0	7.2
1C	HJS	1.1	1.7	2.3	2.8	3.5
3/3A	HRM	1.4	2.4	3.6	4.6	5.9
3/3A	HRS	0.6	1.1	1.7	2.2	2.8
3/3A	HJM	1.1	2.2	3.6	5.0	6.3
3/3A	HJS	0.5	1.0	1.7	2.4	3.0
3B	HRM	4.0	5.0	6.0	7.0	8.0
3B	HRS	1.8	2.3	2.8	3.3	3.8
3B	HJM	3.0	4.5	6.0	7.5	8.5
3B	HJS	1.3	2.1	2.8	3.6	4.1
4	HRM	0.7	1.1	1.5	1.9	2.8
4	HRS	0.3	0.5	0.7	0.9	1.3
4	HJM	0.5	1.0	1.5	2.0	3.0
4	HJS	0.2	0.5	0.7	1.0	1.4

Expert D's Elicitation

Issue 6: Pressure Rise at Vessel Breach for Surry

Description of Expert D's Rationale/Methodology

Expert D concluded that Case 1c was very unlikely to occur because the only way to get a full cavity at Surry is for the sprays to operate in the recirculation mode. He grouped Case 1c with Case 1b. Expert D did not want to group Case 1c with Case 1 because he felt sprays are very important and that spray and no-spray cases should not be grouped together. The sprays can reduce the total resultant pressure by 2.5 bars if the lower base pressure is considered. If the total pressure is close to the failure pressure, this may make an important difference.

Expert D did not consider Case 4 as he felt it was a straight hydrogen burn problem and would produce a minimal threat to the containment. Expert D also grouped Case 1a with Case 1, and Case 3a with Case 3, because he felt the differences between a full cavity and a partially full cavity were not significant. Thus Expert D reduced the cases to four:

<u>Case</u>	<u>RCS Pressure (psia)</u>	<u>Cavity Water</u>	<u>Sprays Operating</u>
1	2000 to 2500	Wet	Yes
1b	2000 to 2500	Dry	No
3	500 to 1000	Wet	Yes
3b	500 to 1000	Dry	No

CONTAIN is currently the only code which has a DCH model, and thus Expert D used the CONTAIN results as the basis for his analysis. The magnitude of the DCH pressure rise depends upon the fraction of the core ejected which is unoxidized metal, primarily zirconium. The initial portion of the ejected material could come from the oxide layer in the lower head of the reactor vessel. A likely scenario has the oxidic material coming out first, immediately followed by steam, and then the metal-rich core debris coming out later. This would give little or no hydrogen production from the particles entrained in the high-velocity steam blowdown.

The heating in DCH comes about one third from the sensible heat in the particles and about two thirds from the chemical reaction (hydrogen production by metal-steam reaction). The effects of metal fraction variation in the ejected material are hard to quantify; a metal-lean mixture could reduce the pressure to 60% of that calculated for the case where the ejected material is homogeneous based on the total core. There are no CONTAIN runs with oxide-rich ejected material to check this.

For the small hole cases, Expert D adjusted the CONTAIN pressures upward somewhat since there is the possibility that more than one penetration may fail at or about the same time.

Considering that the DCH model in CONTAIN is fairly recent, Expert D felt that the number of runs available was large. Variations had been run for the effects of RCS pressure, presence of water in the cavity, amount of zirconium oxidized in the vessel, the melt fraction ejected, and the initial opening size. There were no cases, however, that showed the effects of spray operation at the time of vessel breach.

Expert D defined his base case by starting from the 18-node Surry model with UCHB as defined in Reference D-1. The CONTAIN result, appropriate for Case 1b, showed a peak pressure of 0.93 MPa. Expert D then made several adjustments to this value:

- 0.03 MPa The particle size should be 1 mm based on the SPIT and DCH tests. Agglomeration is neglected in CONTAIN.
- 0.03 Mpa The CONTAIN model should include enhanced trapping.
- 0.05 MPa The effects of the thin steel in the containment will reduce the peak pressure.

Thus Expert D arrived at 0.82 MPa for his base case, best estimate pressure rise. It applies to the subcase with the large fraction of melt ejected (75%) and the small initial hole.

Expert D concluded that the effects of co-dispersed water should not be included for the following reasons:

- For events likely to challenge containment, there will be no sprays operating and the cavity will contain little or no water at vessel breach.
- If there is not much water in the cavity, this water is likely to be blown out of the cavity ahead of the core debris as seen in the "1-s water expulsion cases." (Note: 20,000 kg of water results in about 1 ft of water on the cavity floor.)
- If there is a large amount of water in the cavity, the effect of co-dispersed water, especially with UCHB, will be to reduce the maximum pressure rise observed.

Expert D observed that the fraction of the zirconium oxidized in-vessel was not particularly important. In the CONTAIN run where the in-vessel oxidation was reduced from 50 to 30%, the pressure rise was reduced by only about 0.02 MPa. Therefore, the effects of in-vessel zirconium oxidation will be ignored. The base case has an in-vessel zirconium oxidation of 50%, which is in the middle of the range.

Expert D assumed the following initial conditions:

	<u>With Sprays</u>	<u>Without Sprays</u>
Partial Pressure of Air (psia)	11	12
Partial Pressure of Steam (psia)	4	12
Partial Pressure of H ₂ (psia)	1.7	1.8
Gas Temperature (F)	150	200

The hydrogen partial pressure corresponds to 60% zirconium oxidation, which gives about 950 lb_m. The hydrogen mole fraction in containment would be about 0.10 when the sprays are operating. As any additional hydrogen released would be accompanied by steam at a 2:1 or 3:1 mole ratio, detonation is not credible.

If the sprays are operating, they condense about 500 lb_m of steam per second when the steam concentration is high. About 100 ft³ of liquid water will be airborne in the form of spray droplets at any given time. The droplet surface area will be on the order of 1,000,000 ft². Taking into account that the sprays reduce the initial containment pressure by 0.5 to 1.0 bar relative to the no-spray case, the peak pressure with sprays operating is expected to be about 1.5 to 2.5 bars lower than the equivalent case without the sprays operating.

There is considerable dependence on the particle size in the upward direction. If the particle size assumed in the CONTAIN runs (1.0 mm) is increased, the pressure rise will decrease because the material in the center of the particle will not have reacted before the particle is quenched. That is, for the larger particles, the particle cools off before the zirconium in the center of it reacts with steam. On the other hand, if the particle size is decreased from that assumed in CONTAIN, there is a negligible effect since all the metal in the particle is reacting already.

The SPIT tests showed that 10% of the mass was in particles with an effective mean diameter of greater than 3 mm. Thus there might be a 5% chance that the particles could be large enough so that the hydrogen release is only 10% of what was assumed for the base case, which would reduce the pressure rise to half that of the base case. Note that there is a limit to the upper size of particles because they break up due to impaction or due to internal gas generation.

CONTAIN assumes that the core debris distributed throughout the containment during the blowdown phase of the DCH process is homogeneous. Expert D expects the entrained material to be richer in oxides than a homogenous mixture. That is, he thinks it likely that there will be segregation of the metals from the oxides in the bottom head before vessel failure. The composition of the debris ejected should be correlated with the results of the In-Vessel Panel. At the extreme, 50% of the zirconium could be segregated so that it would exit the vessel after the high velocity gas flow phase of the high pressure melt ejection event. Expert D did not consider it credible that the core debris ejected in the first phase could be rich in unoxidized metal.

Expert D also pointed out that, when DCH occurs, only a very small portion of the hydrogen pre-existing in the containment or produced during the HPME can be expected to remain unburned after the event is over.

Results of Expert D's Elicitation

Base Case. Expert D started with a best estimate of 0.82 MPa for the pressure rise for Case 1b as described above. This value applies to the high fraction ejected and small hole subcase. He multiplied this value by 0.90 since he considered it his best estimate that 20% of the zirconium would be segregated and would not participate in the DCH event. Finally, he multiplied his midpoint value by 0.97 to account for the fact that the hydrogen combustion might not be 100% complete as assumed in CONTAIN. He thus got his 50% probable value of 0.72 MPa.

For the upper bound (95%), he assumed that no zirconium was segregated and that the hydrogen combustion was 100% complete. Thus the zirconium segregation and completeness factors are 1.00. However, for the upper bound case he considered it likely that the particles would have an effective mean diameter of 0.5 mm instead of the 1.0 mm assumed in CONTAIN. This introduces a factor of 1.03. Thus his upper bound for the pressure rise is 0.86 MPa. For the lower bound (5%), he assumed that 50% of the zirconium was segregated and that the hydrogen combustion was 90% complete. The zirconium segregation factor is 0.75 and the completeness factor is 0.90. For the lower bound case Expert D considered it likely that the particles would have an effective mean diameter of 3.0 mm, which introduces a factor of 0.50. Thus his lower bound for the pressure rise is 0.28 MPa. The results of these manipulations can be expressed in tabular form:

Case 1b, High RCS pressure, dry cavity, large fraction ejected, small hole.

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Δp (MPa)	0.82	0.82	0.82
Fraction Ejected Factor	1.0	1.0	1.0
Hole Size Factor	1.0	1.0	1.0
Zr Segregation Factor	0.75	0.90	1.0
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Δp (MPa)	.28	.72	.86

As there are two sizes of hole opening, and three fractions of melt ejected, there are six subcases for the base case, Case 1b. The results are listed on attached Tables D-1 through D-6.

A large part of the pressure rise comes from the hydrogen burn so the pressure rise is not as dependent upon DCH as one might think at first.

Other Cases: Expert D took Case 1b as his base case since that was the one for which the most CONTAIN results were available. He initially put wider distributions on the other cases since he could not start from available CONTAIN results. The factors used to obtain the starting values for pressure rise for the four cases are given on the next page.

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Case (Case 1b)	1.00	1.00	1.00
Case 1	0.70	0.75	0.80
Case 3b	0.75	0.80	0.85
Case 3	0.52	0.60	0.68

These factors are applied to the general base case pressure rise of 0.82 MPa. Case 1b is the most severe since it has the highest RCS pressure and a dry cavity. Case 3 is the least severe (of these four) since it has a lower RCS pressure and a wet cavity. Expert D figured that Case 3 was the most uncertain because he had only to adjust for one factor in going from the base Case (1b) to Case 1 or Case 3b, while he had to adjust two factors (RCS pressure and cavity water) in going from Case 1b to Case 3.

The six subcases for each of the other three cases are contained in Tables D-7 through D-24. The various adjustment factors are applied just as they were for the base case above. The fraction ejected, zirconium segregation, particle size, and completeness factors are independent of case. The hole size factors depend upon the RCS pressure.

The fraction ejected factors are:

<u>Fraction Ejected</u>	<u>Factor</u>
25%	0.80
50%	0.90
75%	1.00

The small hole size factor is 1.00 for all points on the cumulative probability curve. The adjustment factors for the large hole are:

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
High RCS Pressure	1.00	1.10	1.25
Low RCS Pressure	1.00	1.03	1.10

The zirconium segregation factors are:

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Fraction of Zr Segregated	0.50	0.20	0.00
Factor	0.75	0.90	1.00

The particle size adjustment factors are:

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Effective Particle			
Diameter (mm)	3.00	1.00	0.50
Factor	0.50	1.00	1.05

The completeness factors are:

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Factor	0.90	0.97	1.00

These factors have all been applied in the manner described to obtain the resultant pressure rises shown in Tables D-1 through D-24. The pressure rises at vessel breach are summarized in Table D-25.

Sources of Uncertainty

Expert D felt the uncertainty in rates was not so important since most processes went to completion. The variability in the fraction ejected and the hole size have partially been accounted for in the subcase structure. The major uncertainties that cause the broadness of the distributions are the amount of zirconium segregation before breach (or the metal fraction ejected early) and the effective particle size. The effect of incomplete hydrogen combustion is small since it is expected to be very nearly complete in all cases.

Correlations with Other Variables

The amount of unoxidized zirconium in the core debris ejected before the gas blowdown should be correlated with the results of the In-Vessel Panel.

Table D-1
Case 1b: High RCS Pressure and Dry Cavity
Large Fraction Ejected
Small Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.82	0.82	0.82
Fraction Ejected Factor	1.00	1.00	1.00
Hole Size Factor	1.00	1.00	1.00
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.28	0.72	0.86

Table D-2
Case 1b: High RCS Pressure and Dry Cavity
Medium Fraction Ejected
Small Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.82	0.82	0.82
Fraction Ejected Factor	0.90	0.90	0.90
Hole Size Factor	1.00	1.00	1.00
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.25	0.64	0.77

Table D-3
Case 1b: High RCS Pressure and Dry Cavity
Small Fraction Ejected
Small Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.82	0.82	0.82
Fraction Ejected Factor	0.80	0.80	0.80
Hole Size Factor	1.00	1.00	1.00
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.22	0.57	0.69

Table D-4
Case 1b: High RCS Pressure and Dry Cavity
Large Fraction Ejected
Large Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.82	0.82	0.82
Fraction Ejected Factor	1.00	1.00	1.00
Hole Size Factor	1.00	1.10	1.25
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.28	0.79	1.08

Table D-5
Case 1b: High RCS Pressure and Dry Cavity
Medium Fraction Ejected
Large Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.82	0.82	0.82
Fraction Ejected Factor	0.90	0.90	0.90
Hole Size Factor	1.00	1.10	1.25
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.25	0.71	0.97

Table D-6
Case 1b: High RCS Pressure and Dry Cavity
Medium Fraction Ejected
Large Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.82	0.82	0.82
Fraction Ejected Factor	0.80	0.80	0.80
Hole Size Factor	1.00	1.10	1.25
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.22	0.63	0.86

Table D-7
Case 1: High RCS Pressure and Wet Cavity
Large Fraction Ejected
Small Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.57	0.62	0.66
Fraction Ejected Factor	1.00	1.00	1.00
Hole Size Factor	1.00	1.00	1.00
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.19	0.54	0.69

Table D-8
Case 1: High RCS Pressure and Wet Cavity
Medium Fraction Ejected
Small Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.57	0.62	0.66
Fraction Ejected Factor	0.90	0.90	0.90
Hole Size Factor	1.00	1.00	1.00
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.17	0.48	0.62

Table D-9
Case 1: High RCS Pressure and Wet Cavity
Small Fraction Ejected
Small Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.57	0.62	0.66
Fraction Ejected Factor	0.80	0.80	0.80
Hole Size Factor	1.00	1.00	1.00
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.15	0.43	0.55

Table D-10
Case 1: High RCS Pressure and Wet Cavity
Large Fraction Ejected
Large Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.57	0.62	0.66
Fraction Ejected Factor	1.00	1.00	1.00
Hole Size Factor	1.00	1.10	1.25
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.19	0.59	0.86

Table D-11
Case 1. High RCS Pressure and Wet Cavity
Medium Fraction Ejected
Large Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.57	0.62	0.66
Fraction Ejected Factor	0.90	0.90	0.90
Hole Size Factor	1.00	1.10	1.25
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.17	0.53	0.77

Table D-12
Case 1: High RCS Pressure and Wet Cavity
Small Fraction Ejected
Large Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.57	0.62	0.66
Fraction Ejected Factor	0.80	0.80	0.80
Hole Size Factor	1.00	1.10	1.25
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.15	0.47	0.69

Table D-13
Case 3b: Moderate RCS Pressure and Dry Cavity
Large Fraction Ejected
Small Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.62	0.66	0.70
Fraction Ejected Factor	1.00	1.00	1.00
Hole Size Factor	1.00	1.00	1.00
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.21	0.57	0.73

Table D-14
Case 3b: Moderate RCS Pressure and Dry Cavity
Medium Fraction Ejected
Small Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.62	0.66	0.70
Fraction Ejected Factor	0.90	0.90	0.90
Hole Size Factor	1.00	1.00	1.00
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.19	0.52	0.66

Table D-15
Case 3b: Moderate RCS Pressure and Dry Cavity
Small Fraction Ejected
Small Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.62	0.66	0.70
Fraction Ejected Factor	0.80	0.80	0.80
Hole Size Factor	1.00	1.00	1.00
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.17	0.46	0.59

Table D-16
Case 3b: Moderate RCS Pressure and Dry Cavity
Large Fraction Ejected
Large Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.62	0.66	0.70
Fraction Ejected Factor	1.00	1.00	1.00
Hole Size Factor	1.00	1.03	1.10
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.21	0.59	0.81

Table D-17
Case 3b: Moderate RCS Pressure and Dry Cavity
Medium Fraction Ejected
Large Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.62	0.66	0.70
Fraction Ejected Factor	0.90	0.90	0.90
Hole Size Factor	1.00	1.03	1.10
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.19	0.53	0.72

Table D-18
Case 3b: Moderate RCS Pressure and Dry Cavity
Small Fraction Ejected
Large Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.62	0.66	0.70
Fraction Ejected Factor	0.80	0.80	0.80
Hole Size Factor	1.00	1.03	1.10
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.17	0.47	0.64

Table D-19
Case 3: Moderate RCS Pressure and Wet Cavity
Large Fraction Ejected
Small Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.43	0.49	0.56
Fraction Ejected Factor	1.00	1.00	1.00
Hole Size Factor	1.00	1.00	1.00
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.14	0.43	0.59

Table D-20
Case 3: Moderate RCS Pressure and Wet Cavity
Medium Fraction Ejected
Small Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.43	0.49	0.56
Fraction Ejected Factor	0.90	0.90	0.90
Hole Size Factor	1.00	1.00	1.00
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.13	0.39	0.53

Table D-21
Case 3: Moderate RCS Pressure and Wet Cavity
Small Fraction Ejected
Small Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.43	0.49	0.56
Fraction Ejected Factor	0.80	0.80	0.80
Hole Size Factor	1.00	1.00	1.00
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.12	0.34	0.47

Table D-22
Case 3: Moderate RCS Pressure and Wet Cavity
Large Fraction Ejected
Large Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.43	0.49	0.56
Fraction Ejected Factor	1.00	1.00	1.00
Hole Size Factor	1.00	1.03	1.10
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.14	0.44	0.64

Table D-23
Case 3: Moderate RCS Pressure and Wet Cavity
Medium Fraction Ejected
Large Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.43	0.49	0.56
Fraction Ejected Factor	0.90	0.90	0.90
Hole Size Factor	1.00	1.03	1.10
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.13	0.40	0.58

Table D-24
Case 3: Moderate RCS Pressure and Wet Cavity
Small Fraction Ejected
Large Hole Size

	<u>Cumulative Probability</u>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>
Base Pressure Rise (MPa)	0.43	0.49	0.56
Fraction Ejected Factor	0.80	0.80	0.80
Hole Size Factor	1.00	1.03	1.10
Zirconium Segregation Factor	0.75	0.90	1.00
Particle Size Factor	0.50	1.00	1.05
Completeness Factor	0.90	0.97	1.00
Resultant Pressure Rise (MPa)	0.12	0.35	0.52

Table D-25
Loads at Vessel Breach at Surry for Expert D (bars)

Case	Subcase		Fractile				
	Hole Size	Fraction Ejected	0.010*	0.050	0.500	0.950	0.990*
1	High	High	1.5	1.9	5.9	8.6	9.9
1	High	Low	1.2	1.5	4.7	6.9	7.9
1	Low	High	1.6	1.9	5.4	6.9	8.0
1	Low	Low	1.3	1.5	4.3	5.5	6.4
1A	High	High	1.5	1.9	5.9	8.6	9.9
1A	High	Low	1.2	1.5	4.7	6.9	7.9
1A	Low	High	1.6	1.9	5.4	6.9	8.0
1A	Low	Low	1.3	1.5	4.3	5.5	6.4
1B	High	High	2.3	2.8	7.9	10.8	12.4
1B	High	Low	1.8	2.2	6.3	8.6	9.9
1B	Low	High	2.4	2.8	7.2	8.6	10.0
1B	Low	Low	1.9	2.2	5.7	6.9	8.0
1C	High	High	2.3	2.8	7.9	10.8	12.4
1C	High	Low	1.8	2.2	6.3	8.6	9.9
1C	Low	High	2.4	2.8	7.2	8.6	10.0
1C	Low	Low	1.9	2.2	5.7	6.9	8.0
3	High	High	1.1	1.4	4.4	6.4	7.4
3	High	Low	1.0	1.2	3.5	5.2	6.0
3	Low	High	1.1	1.4	4.3	5.9	6.8
3	Low	Low	1.0	1.2	3.4	4.7	5.4
3A	High	High	1.1	1.4	4.4	6.4	7.4
3A	High	Low	1.0	1.2	3.5	5.2	6.0
3A	Low	High	1.1	1.4	4.3	5.9	6.8
3A	Low	Low	1.0	1.2	3.4	4.7	5.4
3B	High	High	1.8	2.1	5.9	8.1	9.3
3B	High	Low	1.4	1.7	4.7	6.4	7.9
3B	Low	High	1.8	2.1	5.7	7.3	8.5
3B	Low	Low	1.4	1.7	4.6	5.9	6.8
4	High	High	0.2	0.4	1.7	3.3	5.2
4	High	Low	0.1	0.3	0.7	1.7	2.6
4	Low	High	0.3	0.6	1.5	3.8	5.8
4	Low	Low	0.1	0.3	0.7	1.5	2.3

*1st and 99th percentiles have been estimated by extrapolation.

REFERENCE

- D-1. D. C. Williams et al., "Containment Loads Due to Direct Containment Heating and Associated Hydrogen Behavior: Analysis and Calculations with the CONTIAN Code," Sandia National Laboratories, NUREG/CR-4896, SAND87-0133, May 1987.

5.7 Containment Loads Issue 7: Pressure Increment in the Zion Containment at Vessel Breach

**Summary of Expert Panel's Assessment of Issue 7:
Pressure Increment in the Zion Containment at Vessel Breach**

Experts consulted: Lou Baker, Argonne National Laboratory; Ken Bergeron, Sandia National Laboratories; Ted Ginsberg, Brookhaven National Laboratory; Marty Plys, Fauske & Associates; Fred Torri, Pickard, Lowe, & Garrick.

Issue Description

What distributions characterize the uncertainty in the pressure increment in the Zion containment at vessel breach?

This issue is concerned with the pressure increment in containment due to depressurization of the RCS, ex-vessel fuel coolant interactions, hydrogen combustion, and DCH. This issue applies to all meltdown scenarios in which the reactor vessel fails and a fraction of the core is ejected. RCS blowdown and DCH cause significant loads to the containment only if the RCS pressure is ten to twenty atmospheres or more above that of the containment at vessel breach. The initial presentation of this issue delineated four RCS pressure ranges for consideration. This was reduced to three pressure ranges, and the case structure for Zion was redefined as follows:

<u>Case</u>	<u>RCS Pressure</u>	<u>Cavity Water (psi)</u>	<u>Sprays Operating</u>
1	2000 to 2500	Full	Yes
1A	2000 to 2500	Half	No
1B	2000 to 2500	Dry	No
3	500 to 1000	Full	Yes
3A	500 to 1000	Half	No
3B	500 to 1000	Dry	No
3C	500 to 1000	Full	No
4	15 to 200	Full	Yes

The panel of five experts collectively determined to provide information based on three additional variables. The variables were: amount of zirconium oxidation: high (50%) and low (25%), melt fraction ejected: high (75%) and low (33%), and initial hole size: large (2 m²) and small (.1 m²). This means there were eight subcases for each of the eight cases above.

Summary of Experts' Rationale

Expert A observed that there was less known about DCH than about the other causes of the pressure rise listed in the issue description. There have been four DCH experiments at Sandia using the Surtsey facility. The initial CONTAIN predictions matched the DCH-1 experiment fairly well, but matched the DCH-2, DCH-3, and DCH-4 tests fairly poorly. A much better match to the later three DCH tests was obtained by changing the trapping parameter in CONTAIN from the value used for the DCH-1 test.

The effects of a full cavity of water are hard to estimate; the water could make the pressure rise larger due to increased steam production, or the water could make the pressure rise smaller due to quenching. Expert A concluded that the median pressure rise for the full cavity case would be slightly higher than for the equivalent case with a dry cavity. The hot gas resulting from vessel breach at any pressure above a few hundred psi will result in ignition if there is enough oxygen and hydrogen for combustion. The combustion should be complete. Expert A concluded that detonations were not likely at Zion. At the time of vessel breach, the pre-existing hydrogen would be cold and would deflagrate while the hydrogen plume from the vessel would be hot and would probably burn as a diffusion flame. At Zion, it is very unlikely that enough hydrogen could accumulate by the time of vessel breach to allow a global detonation. Expert A felt that local detonations could not be ruled out, however, and the possibility of detonations contributed to the spread in his distributions. The detonation mechanism is the failure of ignition or the diffusion flame for a few critical seconds as the hot gas flows out from the hole in the vessel. If this occurs, then detonatable concentrations could exist in a limited volume.

The case structure listed above accounts for variations due to water in the cavity, sprays, and RCS pressure at vessel failure. The subcase structure accounts for differences due to the amount of in-vessel zirconium oxidation, the hole size, and the fraction of mass ejected. Other factors were accounted for by broadening the uncertainty bounds. In the course of this analysis, Expert A concluded that the pressure rise was fairly insensitive to the amount of in-vessel zirconium oxidation. The eight subcases were defined by a three-letter code:

<u>Description</u>	<u>Letter</u>	<u>Word</u>
In-Vessel zirconium oxidation	O	High
	o	Low
Vessel Hole Size	H	Large
	h	Small
Core Fraction Ejected	C	Large
	c	Small

Thus, Case 1B-OHc is Case 1B as defined in Section 1, with high oxidation of zirconium in-vessel, a large hole size, and a small fraction of the core ejected.

Expert A approached the problem by using the available CONTAIN, MAAPI, and Surtsey results to carefully determine pressure rise distributions for three base cases. Using a PC spreadsheet program, he then adjusted these base cases to get values for all the other 61 subcases required.

The extremes of his ranges for the base cases were based on energy balance calculations, which are relatively straightforward. The best estimate is

based on code results, primarily CONTAIN results for Zion* and other CONTAIN results in NUREG/CR-4896.⁴⁻¹ Recent 18-cell CONTAIN results show, for example, that some of the earlier results are too high by about one bar. Expert A spent most of his time on the base cases trying to get the center of his distributions correct, since that is where the bulk of the probability lies. He spent very little time on the low pressure rise end of the curves since he felt that the pressure rises in this region would not fail the containment. He spent a fair amount of time on the upper ends, however, even though containment failure is assured for these pressure rises, because the base case is often reduced in calculating the subsidiary cases. As the base cases were picked to be about the most severe expected for the three RCS pressure levels, the base case is never increased enough in obtaining a derivative case that the low pressure end of the curve becomes important.

Expert B based this assessment on BNL Zion CONTAIN calculations.* The results of both the melt ejection visualization experiments executed at BNL, and the SNL Surtsey experiments were also considered. The BNL calculations utilize an SP1 melt, 22,000 kg of iron and a melt temperature of 2500 K.

Expert B believed that the direct containment heating scenario is typified by certain phenomena. The molten core is expelled from the vessel into the reactor cavity. The blowdown gas then follows and entrains the melt which then exits the cavity in the form of particles, rather than in waves or films. The debris particle droplet size is on the order of tenths of millimeters. The gas is heated as it passes through the melt, causing it to accelerate to velocities of several hundred meters per second. More than 80% of the molten core exits the cavity; there is no freezing of the melt on the cavity walls because the small residence times in the cavity limit crust formation. The zirconium-steam reaction is complete, limited only by steam starvation, and steam can react with up to as much as 50% of the iron in the melt, after the unoxidized zirconium has been consumed.

Expert B began his assessment with a "base case" scenario for Case 1B. Sensitivity variations from that case were then considered with respect to zirconium content, break size, and melt mass. Sensitivity to zirconium content was not demonstrated from BNL CONTAIN calculations, so separate assessments for this parameter were eliminated, and the amount of zirconium unoxidized in the melt was fixed at 50% for the distributions. With the larger hole size, more steam escapes with the molten debris, thus increasing the distribution pressure increment values except for the upper bound, because maximum steam rates were already considered for this value.

Upper bounds were determined by adjusting the median value while considering three separate phenomena. The first adjustment is to allow all the hydrogen generated to be burned. The other two adjustments include increasing the steam blowdown time to equal the melt ejection time and decreasing the trapping rate of the particles.

*T. Ginsberg et al., "CONTAIN Sensitivity Studies of Zion DCH Containment Loadings," Brookhaven National Laboratory, Letter Report, February 26, 1988.

The lower bounds were determined by adjusting the median value for two phenomena. The first is a decrease in the extent of the hydrogen generation; this affects the burn pressure increase. The second is to increase the particle trapping rate to account for larger particles and shorter suspension times.

Expert C concluded that it was impossible to duplicate the codes by hand, or even generate good approximations, so his approach was to take the available code calculations, consider the assumptions made in each code and the assumptions made in the input for the runs available, and then adapt and adjust the results from the codes to get the values required here. He concluded that the code developers and analysts were knowledgeable in the complex physical issues and that they had exercised due diligence in the development and use of the codes. He believed that his role in the elicitation was best served by an interpretation of the codes and available results for the cases at hand. It is impossible to account for all the nonlinearities and interactions in one's head for a problem as complex as this; we rely on the code to do this. A simple approach based on a few hand calculations too risky for such a complex problem.

Expert C relied primarily on MAAP^{C-1} and CONTAIN^{*} calculations. He also utilized the Argonne experiments.^{C-2}

Expert C provided pressure rises for eight subcases for each of the cases defined in Section 1. These subcases are defined by a three-letter code:

<u>Description</u>	<u>Letter</u>	<u>Word</u>
In-vessel zirconium oxidation	H L	High Low
Vessel hole size	R J	Rip Jet
Core fraction ejected	M S	Major Small

That is, Case 3B-HJM is Case 3B as defined, with high oxidation of zirconium in-vessel, a small (Jet) hole size, and a large (Major) fraction of the core ejected.

Expert C tabulated the number of available code results for each case and subcase. There were about a dozen runs each for cases 1B-HJM and 3B-HJM, and two results (each) for cases 1B-HJS and 3B-HJS. The other cases had no code calculations at all. Case 1B is the worst case, i.e., it gives the highest Δp in the containment, so Expert C started with Case 1B-HJM. Results for the subcases for which there were no runs had to be obtained by shifting and scaling from the four cases for which the code results were available.

Expert D performed a thermodynamic calculation for the assessment. The calculation was executed by a short computer program that provided the

^{*T} Ginsberg, Letter, "Brookhaven CONTAIN Calculations," March 1988

values for the medians of the distributions. Internal energy tables were employed in the code execution. An adiabatic energy balance was utilized and so the effect of hole size was not provided, although it was judged that the distribution ranges would incorporate the effect.

Various assumptions were made for the calculations. It was assumed that the core debris is at 2530 K: 0.257 MJ/kg latent heat and 0.943 MJ/kg sensible heat. Between 0 and 20% (depending on the case being assessed) of the ejected core is quenched, producing steam. From results of Surtsey Tests 2, 3, and 4, it is assumed that at least 10% of the ejected core is frozen on the cavity walls. Both zirconium and iron are reacted with steam in creating hydrogen. When hydrogen is produced, 90% of the hydrogen is burned, and the resulting pressure rise is computed (10% is unavailable due to poor mixing in the lower part of the containment where air has been purged by steam blowdown).

Expert D believed that detonations would not occur because unconditional burning of hydrogen together with the rate of hydrogen production and mode of mixing precludes detonatable mixtures. As an informal check, the results of the calculations were compared with Expert B's preliminary CONTAIN results for Zion and it was noted that for the upper limits, the results were in general agreement.

Expert D did bounding calculations for the upper and lower bounds of the distributions (1 and 99 percentiles), by setting credible limits on the metal-steam reactions. The extent of the reaction was then varied to complete the distributions. To establish the lower bound of the distribution, a 25% metal-steam reaction was assumed, and to establish the upper bound, a complete reaction was assumed. In all the distributions, Expert D tended to give a little more weight to the lower values, because the calculation did not include the heat sinks in the containment, which, if included would result in a smaller pressure increment.

For shifting from Case 1 and its subcases to Case 3 and its subcases, Expert D varied the amount of quenching depending on the amount of cavity water. In Case 3, it was assumed that there was less steam blowdown energy than in Case 1, because there is less water inventory and less energy in the primary system at vessel breach. For Case 4, a steam spike was calculated, negligible hydrogen was produced, and no pressure increment from hydrogen burns was computed. The upper bound for Case 4 was determined by assuming complete conversion of core melt energy to steam.

Expert E concluded that the DCH following vessel failure with the vessel at 1000 psi would be significantly different from the DCH following vessel breach at 500 psi. Therefore he split up Case 3 into Case 3 (1000 psi) and Case 5 (500 psi). He concluded that the pressure rise for Case 3C would not differ significantly from that for Case 3, so separate pressure rise values were not given.

Expert E also decided that he could not make meaningful distinctions based on the metallic content of the ejected core material, so he eliminated the fraction of the zirconium oxidized in-vessel as a variable. His subcase structure is defined by a two-letter code:

Vessel hole size	H	Large
	h	Small
Core fraction ejected	C	Large
	c	Small

That is, Case 3B-hC is vessel failure at 1000 psi, dry cavity, no sprays, a small initial hole size, and a large fraction of the core ejected (penetration failure).

Expert E relied primarily on MAAP^{E-1} and CONTAIN^{*} calculations. Results of code calculations were available only for cases 1B-hC, 1B-hc, 3B-hC, and 3B-hc. Most of the results available were for the hC subcase for both Cases 1B and 3B. Therefore, Expert E considered his "base" subcase to be hC: a small hole and a large fraction of core ejected.

Expert E obtained his midpoint values for cases 1B-hC and 3B-hC by weighting the CONTAIN results more or less equally with the MAAP results with UCHB. To obtain his upper bound, he considered the CONTAIN results and physical limitations. He noted that even with very conservative assumptions, the CONTAIN analyses rarely, if ever, got any pressure rises over 12 to 14 bars. The maximum found with the MAAP code was around nine bars. These maxima would probably fail Zion as they started from a base pressure of 2.4 to 2.8 bars, so he felt that the exact maximum pressure rise may not be very important. The lower bound of his distribution for pressure rise is fixed by a steam spike with no hydrogen burn, which results in a one to two bar pressure rise "floor" for all the distributions.

The pressure rise distributions for all the other cases and subcases were determined from these cases by shifting the results of the base cases, scaling the results of the base cases, or both. In applying a shift to the base case, a value was added to the midpoint and upper bound values. In scaling the base case values, the difference between the midpoint value or the upper bound and the lower bound was multiplied by a factor. The lower bound value was usually not affected by these operations since it was fixed by the pressure rise attributable to the steam spike alone. This pressure rise was not affected by the phenomena being accounted for in the shifting and scaling adjustments. If both adjustments were applied, the shifting adjustment was applied first.

In going from the dry cavity cases where there were code runs available to the wet cavity cases where there were no code results, Expert E concluded that the upper bound would not be affected since it is possible that the water in the cavity might all be expelled from it before the DCH portion of the event commenced. He considered it more likely that some quenching would occur, however, and that the midpoint value for the wet cavity Case would be reduced one to two bars below the value for the equivalent dry cavity case. For the partially-full cavity cases, Expert E considered that water expulsion was more likely than in the full cavity case. The midpoint pressure rise values for these cases he set at 0.5 to 1.0 bars below the value for the equivalent dry cavity case.

*T. Ginsberg, Letter, "Brookhaven CONTAIN Calculations," March 1988.

Method of Aggregation

The data were analyzed as a "block factorial" or "factorial repeated measures" experiment, that is, an experiment having more than one type of treatment, in which every combination of treatment levels is applied to each subject. Initially, the treatment types were considered to be "cases," with eight levels, and "subcases," with eight levels (corresponding to combinations of low and high fraction ejected with large and small hole areas, and with high and low zirconium oxidation levels). An analysis of variance (ANOVA) was carried out on the data for the 1st, 50th, and 99th percentiles of the experts' distributions.^{A-1} An ANOVA compares two independent estimates of the population variance: one computed from the treatment means (i.e., the "between treatments" variance), and the other as the "within treatments" variance. This is equivalent to comparing the variance in the dependent variable attributable to the treatments with the unexplained (residual) variance.

The differences between experts are indeed significant. There are no significant case-by-subcase interactions, indicating that the experts applied the subcase variations consistently to each case.

Main effects' contrasts for cases were tested. "Main effects" are the means of the dependent variable (the pressure increment) averaged over all subcases and experts for each case. The differences between main effects means were tested by a Least Significant Difference (LSD) test. The LSD is the smallest absolute value of the differences between two means which should be considered significant. In order to retain as many cases as necessary, the significance level for the LSD test was set quite high (20%). The ANOVA showed that Cases 1A and 1B can be combined, as can 3A, 3B, and 3C.

To test the differences attributable to individual subcases within a case, a simple main effects ANOVA was performed. This ANOVA compares the variance attributable to the subcases evaluated at each of the cases to the residual variance. At least for the 50th and 99th percentiles, some subcases are significantly different for Case 1 through Case 3C. For Case 4, however, there is no significant difference at any level. All subcases can thus be combined for Case 4, but only the high and low zirconium oxidation subcases can be combined for the other cases.

There were originally 64 subcases. When zirconium oxidation levels are combined the number drops to 32. If Cases 1A and 1B, and 3A, 3B, and 3C are combined and subcase distinctions are dropped for Case 4, the total number of distinct subcases is 17. Each expert's data for Cases 1A and 1B, and 3A, 3B, and 3C were averaged, as were subcases for Case 4. Table 7-1 gives a description of the 17 new cases in terms of RCS pressure, amount of cavity water, whether the sprays are operating, the core fraction ejected, and the vessel hole size.

Table 7-1
Characteristics of Combined Cases

<u>Case</u>	<u>RCS Pressure</u>	<u>Cavity Water</u>	<u>Sprays Operating</u>	<u>Core Fraction Ejected</u>	<u>Vessel Hole Size</u>
1	High ^a	Full	Yes	High ^b	Large ^c
2	High	Full	Yes	High	Small ^d
3	High	Full	Yes	Low ^e	Large
4	High	Full	Yes	Low	Small
5	High	Half/Dry	No	High	Large
6	High	Half/Dry	No	High	Small
7	High	Half/Dry	No	Low	Large
8	High	Half/Dry	No	Low	Small
9	Med ^f	Full	Yes	High	Large
10	Med	Full	Yes	High	Small
11	Med	Full	Yes	Low	Large
12	Med	Full	Yes	Low	Small
13	Med	Half/Dry	No	High	Large
14	Med	Half/Dry	No	High	Small
15	Med	Half/Dry	No	Low	Large
16	Med	Half/Dry	No	Low	Small
17	Low ^g	--	--	--	--

^a2000 to 2500 psi

^b75%

^c2 m²

^d0.1 m²

^e33%

^f500-1000 psi

^g50-200 psi

Aggregated Results

The final step was to obtain an aggregate set of values for each of the 17 cases; for each pressure increment value, probabilities were determined for each expert by interpolation, and the probabilities were then averaged. Interpolation was then used on the aggregated CDFs to find values for the 1st, 5th, 25th, 50th, 75th, 95th, and 99th percentiles, for each case. In view of the large differences between experts, it is unnecessary to use a finer subdivision of the CDF than this. Table 7-2 shows the results for the final CDFs and Figure 7-1 shows the aggregate for Case 1 (high RCS pressure, full cavity water, sprays operating, high fraction of core ejected, and large vessel hole).

Table 7-2
Aggregate Results: Pressure Rise
at Vessel Breach at Zion (bars)

Case	Fractile								
	0.01	0.05	0.10	0.25	0.50	0.75	0.90	0.95	0.99
1	1.33	2.39	3.23	5.12	6.68	7.95	9.57	10.67	12.11
2	1.24	2.09	2.69	4.05	6.03	7.10	8.25	9.67	11.17
3	1.20	2.03	2.49	3.51	4.55	5.60	6.48	6.97	7.66
4	1.11	1.82	2.20	2.94	4.05	4.86	5.63	6.43	7.62
5	1.91	2.85	3.77	5.83	7.38	8.52	9.66	10.27	11.30
6	1.84	2.56	3.18	4.75	6.72	7.80	8.60	9.26	10.64
7	1.85	2.43	2.94	4.02	4.97	5.86	6.82	7.26	7.96
8	1.48	2.03	2.43	3.36	4.51	5.40	6.14	6.52	7.30
9	1.19	1.97	2.54	3.66	5.32	6.45	7.34	8.14	9.60
10	0.96	1.67	2.06	2.93	4.48	6.00	6.90	7.71	9.57
11	1.04	1.63	1.99	2.70	3.65	4.49	5.14	5.48	5.92
12	0.91	1.25	1.52	2.21	3.13	3.97	4.46	4.73	5.22
13	2.00	2.50	3.00	4.14	5.99	7.13	7.92	8.50	9.62
14	1.42	2.08	2.48	3.36	5.02	6.59	7.41	7.79	9.04
15	1.67	2.07	2.31	2.96	4.02	4.78	5.26	5.58	5.99
16	1.07	1.67	1.96	2.46	3.48	4.34	4.88	5.16	5.64
17	0.45	0.75	0.92	1.22	1.75	2.48	3.02	3.34	4.28

For use in the user function of the APET, the fraction of melt ejected was divided into three groups: 0 to 20%, 20 to 40%, and 40 to 60%. The reason for doing this is that the dividing point between high and low fraction ejected (50% ejected) used by the Containment Loads Expert Panel turns out to be very near the high end of the aggregate distribution given for the fraction of melt ejected by the In-Vessel Expert Panel. If the high-low division given by the Containment Loads Expert Panel was used, over 80% of the cases would fall in the low category.

Since it was not possible to get the Containment Loads Expert Panel to evaluate a new set of distributions, the data are manipulated in the following way. For the 20 to 40% ejected group, the low-fraction-ejected results from the Containment Loads Expert Panel can be used directly since the nominal value used by the Containment Loads experts was 33% ejected. For the 40 to 60% ejected group, the loads low-fraction-ejected and high-fraction-ejected can be averaged. The average of the nominal fractions ejected is 54%, which is reasonably close to the center of this group. For the 0 to 20% ejected group, the average of the low fraction results and the Case 4 results (< 200 psia) can be used.

Figure 7-1. Aggregate of Zion Containment Loading for Case 1.

Table 7-3 gives the new description of the, now, 25 cases in terms of RCS pressure, amount of cavity water, whether the sprays are operating, the core fraction ejected, and the vessel's hole size. Table 7-4 shows the aggregate results for the pressure rise at Zion (Table 7-2) expanded to three fraction-ejected groups by the method described above. Table 7-5 is Table 7-4, with the units converted from bars to psi for direct comparison with the results of the Structural Response Expert Panel. Figure 7-2 is the same as Figure 7-1 but with the revised aggregate distribution used for the 40 to 60% ejected group also included.

Table 7-3
 Characteristics of Combined Cases
 Expanded from Table 7-1

<u>Case</u>	<u>RCS Pressure</u>	<u>Cavity Water</u>	<u>Sprays Operating</u>	<u>Core Fraction Ejected</u>	<u>Vessel Hole Size</u>
1	High ^a	Full	Yes	High ^b	Large ^c
2	High	Full	Yes	High	Small ^d
3	High	Full	Yes	Medium ^e	Large
4	High	Full	Yes	Medium	Small
5	High	Full	Yes	Low ^f	Large
6	High	Full	No	Low	Small
7	High	Half/Dry	No	High	Large
8	High	Half/Dry	No	High	Small
9	High	Half/Dry	No	Medium	Small
10	High	Half/Dry	No	Medium	Small
11	High	Half/Dry	No	Low	Large
12	High	Half/Dry	No	Low	Small
13	Med ^a	Full	Yes	High	Large
14	Med	Full	Yes	High	Small
15	Med	Full	Yes	Medium	Large
16	Med	Full	Yes	Medium	Small
17	Med	Full	Yes	Low	Large
18	Med	Full	Yes	Low	Small
19	Med	Half/Dry	No	High	Large
20	Med	Half/Dry	No	High	Small
21	Med	Half/Dry	No	Medium	Large
22	Med	Half/Dry	No	Medium	Small
23	Med	Half/Dry	No	Low	Large
24	Med	Half/Dry	No	Low	Small
25	Low ^h	--	--	--	--

*2000 to 2500psi

^b40 to 60%

^c2 m²

^d0.1 m²

*20 to 40%

^f0 to 20%

*500 to 1000 psi

^h50 to 200 psi

Table 7-4
Aggregate Results; Pressure Rise
at Vessel Breach at Zion (bars)

Case	Fractile								
	0.01	0.05	0.10	0.25	0.50	0.75	0.90	0.95	0.99
1	1.27	2.21	2.86	4.32	5.62	6.78	8.02	8.82	9.89
2	1.18	1.96	2.45	3.50	5.04	5.98	6.94	8.05	9.40
3	1.20	2.03	2.49	3.51	4.55	5.60	6.48	6.97	7.66
4	1.11	1.82	2.20	2.94	4.05	4.86	5.63	6.43	7.62
5	0.83	1.39	1.71	2.37	3.15	4.04	4.75	5.15	5.97
6	0.78	1.29	1.56	2.08	2.90	3.67	4.33	4.88	5.95
7	1.88	2.64	3.36	4.93	6.18	7.19	8.24	8.77	9.63
8	1.66	2.30	2.81	4.05	5.62	6.60	7.37	7.89	8.97
9	1.85	2.43	2.94	4.02	4.97	5.86	6.82	7.26	7.96
10	1.48	2.03	2.43	3.36	4.51	5.40	6.14	6.52	7.30
11	1.15	1.59	1.93	2.62	3.36	4.17	4.92	5.30	6.12
12	0.97	1.39	1.68	2.29	3.13	3.94	4.58	4.93	5.79
13	1.12	1.80	2.27	3.18	4.49	5.47	6.24	6.81	7.76
14	0.94	1.46	1.79	2.57	3.81	4.99	5.68	6.22	7.39
15	1.04	1.63	1.99	2.70	3.65	4.49	5.14	5.48	5.92
16	0.91	1.25	1.52	2.21	3.13	3.97	4.46	4.73	5.22
17	0.75	1.19	1.46	1.96	2.70	3.48	4.08	4.41	5.10
18	0.68	1.00	1.22	1.72	2.44	3.23	3.74	4.03	4.75
19	1.84	2.29	2.65	3.55	5.01	5.96	6.59	7.04	7.80
20	1.25	1.88	2.22	2.91	4.25	5.47	6.14	6.47	7.34
21	1.67	2.07	2.31	2.96	4.02	4.78	5.26	5.58	5.99
22	1.07	1.67	1.96	2.46	3.48	4.34	4.88	5.16	5.64
23	1.06	1.41	1.62	2.09	2.88	3.63	4.14	4.66	5.14
24	0.76	1.21	1.44	1.84	2.62	3.41	3.95	4.25	4.96
25	0.45	0.75	0.92	1.22	1.75	2.48	3.02	3.34	4.28

Table 7-5
Aggregate Results; Pressure Rise
Vessel Breach at Zion (psig)

Case	Fractile								
	0.01	0.05	0.10	0.25	0.50	0.75	0.90	0.95	0.99
1	18.34	32.05	41.47	52.57	81.42	98.24	116.36	127.89	143.33
2	17.04	28.35	35.45	50.68	73.08	86.71	100.63	116.73	136.23
3	17.40	29.43	36.10	50.90	65.98	81.20	93.96	101.06	111.07
4	16.09	26.39	31.90	42.63	58.73	70.47	81.64	93.24	110.49
5	11.96	20.16	24.72	34.29	45.68	58.58	68.88	74.75	86.57
6	11.31	18.63	22.62	30.16	42.05	53.22	62.71	70.83	86.28
7	27.26	38.28	48.65	71.41	89.54	104.26	119.48	127.09	139.63
8	24.07	33.28	40.67	58.80	81.42	95.70	106.87	114.41	130.07
9	26.83	35.24	42.63	58.29	72.06	84.97	98.89	105.27	115.42
10	21.46	29.43	35.24	48.72	65.40	78.30	89.03	94.54	105.85
11	16.67	23.06	27.99	37.99	48.72	60.47	71.34	76.85	88.74
12	13.99	20.16	24.29	33.20	45.39	57.13	66.41	71.49	83.96
13	16.17	26.10	32.84	46.11	65.03	79.31	90.48	98.75	112.52
14	13.56	21.17	25.95	37.27	55.17	72.28	82.36	90.19	107.23
15	15.08	23.64	28.85	39.15	52.93	65.10	74.53	79.46	85.84
16	13.20	18.13	22.04	32.05	45.39	57.56	64.67	68.58	75.69
17	10.80	17.26	21.10	28.42	39.15	50.53	59.16	63.94	73.95
18	9.86	14.50	17.69	24.87	35.38	46.76	54.23	58.51	68.88
19	26.61	33.13	38.50	51.47	72.57	86.35	95.56	102.08	113.17
20	18.05	27.19	32.19	42.19	61.63	79.24	89.10	93.89	106.43
21	24.22	30.01	33.49	42.92	58.29	69.31	76.27	80.91	86.85
22	15.52	24.22	28.42	35.67	50.46	62.93	70.76	74.82	81.78
23	15.37	20.44	23.42	30.31	41.83	52.64	60.03	64.67	74.46
24	11.02	17.55	20.88	26.68	37.92	49.44	57.28	61.63	71.92
25	6.52	10.88	13.34	17.69	25.38	35.96	43.79	48.43	62.06

Figure 7-2. Revised Aggregate of Zion Containment Loading for Case 1.

Individual Elicitations of Issue 7

Expert A's Elicitation

Issue 7: Pressure Rise At Vessel Breach for Zion

Description of Expert A's Rationale/Methodology

Expert A observed that there was less known about DCH than about the other causes of the pressure rise listed above. There have been four DCH experiments at Sandia using the Surtsey facility. The initial CONTAIN predictions matched the DCH-1 experiment fairly well, and matched the DCH-2, DCH-3, and DCH-4 tests poorly. A much better match to the later three DCH tests was obtained by changing the trapping parameter in CONTAIN from the value used for the DCH-1 test.

The effects of a full cavity of water are hard to estimate; the water could make the pressure rise larger due to increased steam production, or the water could make the pressure rise smaller due to quenching. Expert A concluded that, for Sequoyah, the median pressure rise for the full cavity case would be slightly higher than for the equivalent case with a dry cavity.

The hot gas resulting from vessel breach at any pressure above a few hundred psia will result in ignition if there is enough oxygen and hydrogen for combustion. The combustion should be complete. Expert A concluded that detonations were not likely at Zion. At the time of vessel breach, the pre-existing hydrogen would be cold and would deflagrate while the hydrogen plume from the vessel would be hot and would probably burn as a diffusion flame. At Zion, it is very unlikely that enough hydrogen could accumulate by the time of vessel breach to allow a global detonation. Expert A felt that local detonations could not be ruled out, however, and the possibility of detonations contributed to the spread in his distributions. The detonation mechanism is the failure of ignition or the diffusion flame for a few critical seconds as the hot gas flows out from the hole in the vessel. If this occurs, then detonable concentrations could exist in a limited volume.

The case structure listed above accounts for variations, in a coarse fashion, due to water in the cavity, sprays, and RCS pressure at vessel failure. The subcase structure accounts for differences due to the amount of in-vessel zirconium oxidation, the hole size, and the fraction of mass ejected. Other factors were accounted for by broadening the uncertainty bounds. In the course of this analysis, Expert A concluded that the pressure rise was fairly insensitive to the amount of in-vessel zirconium oxidation. The eight subcases are defined by a three-letter code:

<u>Position</u>	<u>Description</u>	<u>Letter</u>	<u>Word</u>	<u>Nominal</u>	<u>Range</u>
First	In-Vessel Zr Oxidation	O	High	60%	40-80%
		o	Low	25%	10-40%
Second	Vessel Hole Size	H	Large	2 m ²	>0.5 m ²
		h	Small	.1 m ²	<0.5 m ²
Third	Core Fraction Ejected	C	Large	75%	>50%
		c	Small	33%	< 50%

Expert A denoted his Zion cases with the letter "Z". Thus, Case Z3b-OHc is Case 3b as defined above, with high oxidation of zirconium in-vessel, a large hole size, and a small fraction of the core ejected.

Expert A approached the problem by using the available CONTAIN, MAAP, and Surtsey results to carefully determine pressure rise distributions for three base cases. Using a PC spreadsheet program, he then adjusted these base cases to get values for all the other 61 subcases required.

The extremes of his ranges for the base cases were based on relatively straightforward energy balance calculations. The best estimate is based on code results, primarily CONTAIN results for Zion* and other CONTAIN results in NUREG/CR-4896.^{A-1} Recent 18-cell CONTAIN results show that some of the earlier results are too high by about 1.0 bar. Expert A spent most of his time on the base cases trying to get the center of his distributions correct, since that is where the bulk of the probability lies. He took very little time with the low pressure rise end of the curves since the pressure rises in this region will not fail the containment. He spent a fair amount of time on the upper ends, however, even though containment failure is assured for these pressure rises, because the base case is often reduced in calculating the subsidiary cases. As the base cases were picked to be about the most severe expected for the three RCS pressure levels, the base case is never increased enough in obtaining a derivative case that the low pressure rise end of the curve becomes important.

For Zion, Expert A selected three base cases, denoted 1Z, 2Z, and 3Z. The full designation for each case and the reason it was selected are:

<u>Base</u>	<u>Identifier</u>	<u>Reason for Selection</u>
1Z	Z1-oHC	Full cavity more likely than dry cavity at Zion
2Z	Z3b-oHC	Dry cavity case has highest pressure rise
3Z	Z4-oHC	Parallel parameter choice

*T. Ginsberg et al., "CONTAIN Sensitivity Studies of Zion DCH Containment Loadings," Brookhaven National Laboratory, Letter Report, February 26, 1988.

Base Case 1Z: 2000 to 2500 psia in RCS, cavity full, and sprays operating. The subcase is low zirconium oxidation in vessel, a large hole, and large fraction of core ejected. The middle part of Expert A's pressure rise distribution for base Case 1Z is based on the A series of CONTAIN runs made at Brookhaven for Zion* and Cases 17 and 19 in NUREG/CR-4896.^{A-1} The values from the Brookhaven runs were adjusted to account for the fraction of the core participating in DCH from 75% because the Surtsey tests showed that not all the core participated.^{A-2 to A-5} Other adjustments were made to account for the results of the 18-cell runs, sprays, and the effects of co-dispersed water.^{*} After other adjustments for the zirconium oxidation fraction and trapping, Expert A arrived at a median value of 6.5 bars.

The following is Expert A's complete pressure rise distribution for base Case 1Z:

Cum. Prob.	0.01	0.05	0.25	0.50	0.75	0.95	0.99
Δp (bars)	1.5	3.0	4.5	6.5	8.0	9.0	10.0

For his base Case 1Z, Expert A got a range from 1.5 to 10 bars with the median at 6.5 bars. Note that these are pressure rises, not total resultant pressure as reported in Reference A-1. Specific reasoning, with detailed references, are available for each value given above in the notes of Expert A, which are too voluminous to be included here.

Expert A chose his upper and lower bounds based on the report of the Containment Loads Working Group and other calculations and analyses.

Base Case 2Z: 500 to 1000 psia in RCS, cavity dry, and no sprays. The subcase is low zirconium oxidation, large hole, and large fraction of core ejected. This is also denoted Case Z3b-oHC. The pressure rise distribution for this base case is primarily based on the B series of CONTAIN runs made at Brookhaven for Zion** and analogous CONTAIN runs made for Zion for this project.^{***} For the middle values, the adjustments made to the intermediate pressure result from this reference are much the same as those made for the middle values in base Case 1Z. The median and upper bounds are somewhat lower than in base Case 1Z because of the lower pressure in the RCS at the time of vessel failure.

Expert A observed that, for Zion, the presence of water in the cavity increases the peak pressures when the RCS pressure is high before VB, but for intermediate pressures, as here, the presence of water decreases the resulting containment pressures. This is different from the behavior expected for Sequoyah, but is similar to the situation at Surry. The

*Co-dispersed Water Case, Appendix to T. Ginsberg's Letter Report below.

**T. Ginsberg et al., "CONTAIN Sensitivity Studies of Zion DCH Containment Loadings," Brookhaven National Laboratory, Letter Report, February 26, 1988.

***D. C. Williams, "Update on CONTAIN DCH Calculations for Surry," Letter Report to NUREG-1150 Containment Loads Panel, January 11, 1988.

reason is that the cavities at Surry and Zion hold considerably less water than the cavity at Sequoyah. The presence of sprays and water in the cavity inhibit the pressure rise more effectively for intermediate pressure in the RCS (base Case 22) than they do when there is full system pressure in the RCS at breach (base Case 12).

Expert A arrived at the following pressure rise distribution for base Case 22:

Cum. Prob.	0.01	0.05	0.25	0.50	0.75	0.95	0.99
Δp (bars)	2.0	3.0	4.0	5.5	6.8	8.0	9.0

Both the median and the upper bound are 1.0 bar less than their counterpart pressure rises in base Case 12. There are several threshold effects which are difficult to account for satisfactorily. For example, either the pre-existing hydrogen is already burned or it is not, and either quenching occurs or it does not.

Base Case 32: less than 200 psia in RCS, full cavity, and sprays operating. The subcase is low zirconium oxidation, large hole, and large fraction of core ejected. This is also denoted Case Z4-oHC. The pressure rise in this Case is due to phenomena other than DCH: steam spike, molten core-coolant interaction, and hydrogen combustion. DCH is negligible at these low RCS pressures. The distribution for pressure rise is largely derived from the various cases considered by the Containment Loads Working Group. The cases on which the middle and high end of the distribution rely on HECTR results while the low end is reflects the pressure rise due to the steam spike alone.

Expert A arrived at the following pressure rise distribution for base Case 32:

Cum. Prob.	0.01	0.05	0.25	0.50	0.75	0.95	0.99
Δp (bars)	0.3	0.8	1.2	1.5	2.5	5.0	6.0

Expert A derived the pressure rise distributions for all the other cases by means of adjustments to the three base cases described above. These adjustments and the reasoning behind them are described in Expert A's notes which are not included here. As an example, in obtaining the small fraction of core ejected cases from the large fraction of core ejected cases, he reduced the median pressure rise since reducing the fraction of the core ejected in various CONTAIN runs showed such an effect.

Results of Expert 's Elicitation

Expert A provided a table giving the 1%, 5%, 25%, 50%, 75%, 95%, and 99% values for 64 cases and subcases. For listing here, only the 5%, 50% and 95% values are shown. Expert A concluded that the effects of the amount of in-vessel zirconium oxidation could not be distinguished in the presence of other uncertainties for the Z1 and Z3 cases. Thus his results for Z1a-oHC are the same as for Z1a-oHC, for example. Therefore, this variable has been eliminated and only four subcases (HC, hC, Hc, and hc) are shown for cases Z1, Z1a, Z1b, Z3, Z3a, Z3b, and Z3c in the

following table. He also concluded that only the effects of the amount of core ejected could be distinguished in the presence of other uncertainties for Case Z4. Therefore, the other two variables have been eliminated and only two subcases (C and c) are shown for Z4 in the following table. The pressure rises in the following table are in bars.

<u>Case</u>	<u>1%</u>	<u>50%</u>	<u>99%</u>	<u>Case</u>	<u>1%</u>	<u>50%</u>	<u>99%</u>
Z1 -HC	3.0	6.5	9.0	Z1 -Hc	2.3	4.9	6.8
Z1 -hC	2.6	5.5	7.6	Z1 -hc	1.9	4.1	5.7
Z1a-HC	3.6	7.8	9.9	Z1a-Hc	2.7	5.9	7.4
Z1a-hC	3.1	6.6	8.4	Z1a-hc	2.3	5.0	6.3
Z1b-HC	3.6	6.5	10.8	Z1b-Hc	2.7	4.9	8.1
Z1b-hC	3.1	5.5	9.2	Z1b-hc	2.3	4.1	6.9
Z3 -HC	2.4	4.4	7.2	Z3 -Hc	1.7	3.1	5.0
Z3 -hC	1.9	3.5	5.8	Z3 -hc	1.3	2.5	4.0
Z3a-HC	3.3	6.1	8.8	Z3a-Hc	2.3	4.2	6.2
Z3a-hC	2.6	4.8	7.0	Z3a-hc	1.8	3.4	4.9
Z3b-HC	3.0	5.5	8.0	Z3b-Hc	2.1	3.8	5.6
Z3b-hC	2.4	4.4	6.4	Z3b-hc	1.7	3.1	4.5
Z3c-HC	2.6	4.7	7.6	Z3c-Hc	1.8	3.3	5.3
Z3c-hC	2.4	3.7	6.1	Z3c-hc	1.4	2.6	4.3
Z4 -C	0.8	1.5	5.0	Z4 -c	0.6	1.1	3.5

Sources of Uncertainty

Expert A emphasized that there were many uncertainties in estimating containment loads, especially containment loads at vessel breach. Self-heating of the molten material as it travels from the vessel throughout containment is not accounted for in the lumped-parameter codes. This phenomenon is not captured in the Brookhaven experiments. Entrainment and Weber break-up are not mechanistically treated in the detailed codes. A zirconium oxide crust on the ejected droplets may cause them to behave like solid particles rather than liquid particles. Internal gas generation may fragment the droplets, thus affecting the particle size distribution.

Nitrogen chemistry is not included in any of the models. If nitrogen combines with the metal oxides in the droplet, the flow of nitrogen into the droplet may cause fragmentation if the nitrogen is subsequently released. The interactions of corium droplets with surfaces are not well understood; while it is known that molten corium does not wet concrete surfaces, and concrete spalls when covered with enough molten corium, exactly how the corium droplets will interact with concrete surfaces in a DCH event is unknown. The DCH experiments have shown that there is considerable variability in trapping rates. Finally, the flow paths in the containment may change during the event as a result of the event itself.

REFERENCES

- A-1. D. C. Williams et al., "Containment Loads Due to Direct Containment Heating and Associated Hydrogen Behavior: Analysis and Calculations with the CONTAIN Code," Sandia National Laboratories, NUREG/CR-4896, SAND87-0633, May 1987.
- A-2. M. Pilch and W. W. Tarbell, "Preliminary Calculations on Direct Heating of a Containment Atmosphere by Airborne Debris," Sandia National Laboratories, NUREG/CR-4455, SAND85-2439, July 1986.
- A-3. W. W. Tarbell et al., "Results From the DCH-1 Experiment," Sandia National Laboratories, NUREG/CR-4871, SAND86-2483, June 1987.
- A-4. M. Pilch and W. W. Tarbell, "High Pressure Ejection of Melt From a Reactor Pressure Vessel," Sandia National Laboratories, NUREG/CR-4383, SAND85-0012, September 1985.
- A-5. W. W. Tarbell, "Pressurized Melt Ejection Into Sealed Reactor Cavities," Sandia National Laboratories, NUREG/CR-4512, SAND86-0153, October 1986.

Expert B's Elicitation

Issue 7: Pressure Rise at Vessel Breach for Zion

Description of Expert B's Rationale/Methodology

Expert B based the assessment on BNL's CONTAIN calculations for Zion. The results of both the melt ejection visualization experiments executed at BNL, and the Sandia Surtsey experiments were also considered. The BNL calculations utilize an SP1 melt--22,000 kg of iron and a melt temperature of 2500 K.

Expert B believes that the direct containment heating scenario is typified by certain phenomena. The molten core is expelled from the vessel into the reactor cavity. The blowdown gas then follows and entrains the melt which then exits the cavity in the form of particulate, rather than in waves or films. The debris particulate droplet size is on the order of tenths of millimeters. The gas is heated as it passes through the melt, causing it to accelerate to velocities of several hundred meters per second. More than 80% of the molten core exits the cavity, there is no freezing of the melt on the cavity walls because the small residence times in the cavity limit crust formation. The zirconium-steam reaction is complete, limited only by steam starvation, and steam can react with up to as much as 50% of the iron in the melt, after the unoxidized zirconium has been consumed.

Expert B approached the assessment with a "base case" scenario, Case 1b. Sensitivity variations from that case were then considered with respect to zirconium content, break size and melt mass. From BNL CONTAIN calculations, sensitivity to zirconium content was not demonstrated, so separate assessments for this parameter were eliminated, and the amount of zirconium unoxidized in the melt was fixed at 50% for the distributions. For the larger hole size, more steam escapes with the molten debris, thus increasing the distribution pressure increment values except for the upper bound, because maximum steam rates are already considered for this value.

Upper bounds were determined by adjusting the median value considering three separate phenomena. The first adjustment is to allow all the hydrogen generated to be burned. The other two adjustments include increasing the steam blowdown time to equal the melt ejection time and decreasing the trapping rate of the particles.

The lower bounds were determined by adjusting the median value for two phenomena. The first is a decrease in the extent of the hydrogen generation--this affects the burn pressure increase. The second is to increase particle trapping rate to account for larger particles and shorter suspension times.

Results of Expert B's Elicitation

The distributions are provided in Table B-1 for Cases 1, 1a, and 1b, in Table B-2 for Cases 3, 3a, 3b, and 3c, and in Table B-3 for Case 4.

Table B-1
Pressure Increment in the Zion Containment at Vessel Breach

<u>Melt Hole</u>			<u>Cumulative Probabilities</u>						
<u>Case</u>	<u>Melt Mass (%)</u>	<u>Hole Area (M²)</u>	<u>.1%</u>	<u>1%</u>	<u>5%</u>	<u>50%</u>	<u>95%</u>	<u>99%</u>	<u>99.9%</u>
<u>Pressure Increment (bar)</u>									
1	75	0.1	1.5	3.0	4.0	8.0	11.0	12.0	14.0
1	75	2.0	1.5	4.0	5.0	9.0	12.0	13.0	14.0
1	25	0.1	1.0	1.5	2.5	5.0	7.5	8.3	8.5
1	25	2.0	1.0	2.0	3.5	6.0	7.5	8.3	8.5
1a	75	0.1	1.5	3.0	4.0	8.0	11.0	12.0	14.0
1a	75	2.0	1.5	4.0	5.0	9.0	12.0	13.0	14.0
1a	25	0.1	1.0	1.5	2.5	5.0	7.5	8.3	8.5
1a	25	2.0	1.0	2.0	3.5	6.0	7.5	8.3	8.5
1b	75	0.1	1.5	4.0	6.0	7.0	10.0	12.0	14.0
1b	75	2.0	1.5	5.0	7.0	8.0	10.0	12.0	14.0
1b	25	0.1	1.0	2.0	3.5	4.5	7.0	7.8	8.5
1b	25	2.0	1.0	2.0	3.5	4.5	7.0	7.8	8.5

Table B-2
Pressure Increment in the Zion Containment at Vessel Breach

<u>Melt Hole</u>			<u>Cumulative Probabilities</u>						
<u>Case</u>	<u>Melt Mass (%)</u>	<u>Hole Area (M²)</u>	<u>.1%</u>	<u>1%</u>	<u>5%</u>	<u>50%</u>	<u>95%</u>	<u>99%</u>	<u>99.9%</u>
<u>Pressure Increment (bar)</u>									
3	75	0.1	0.5	0.8	1.5	5.5	9.3	11.4	13.0
3	75	2.0	0.5	1.5	2.5	6.5	9.3	11.4	13.0
3	25	0.1	0.5	0.8	1.0	3.5	4.8	6.0	7.5
3	25	2.0	0.5	1.8	2.0	4.5	5.5	6.0	7.5

Table B-2 (continued)

<u>Melt Hole</u>			<u>Cumulative Probabilities</u>						
<u>Case</u>	<u>Melt Mass (%)</u>	<u>Hole Area (M^2)</u>	<u>.1%</u>	<u>1%</u>	<u>5%</u>	<u>50%</u>	<u>95%</u>	<u>99%</u>	<u>99.9%</u>
<u>Pressure Increment (bar)</u>									
3a	75	0.1	0.5	0.8	1.5	5.5	9.3	11.4	13.0
3a	75	2.0	0.5	1.5	2.5	6.5	9.3	11.4	13.0
3a	25	0.1	0.5	0.8	1.0	3.5	4.8	6.0	7.5
3a	25	2.0	0.5	1.8	2.0	4.5	5.5	6.0	7.5
3b	75	0.1	0.5	1.0	2.0	4.5	8.3	10.4	13.0
3b	75	2.0	1.5	4.0	5.0	7.0	10.0	12.0	14.0
3b	25	0.1	0.5	1.0	1.5	2.5	4.8	6.0	7.5
3b	25	2.0	0.5	2.0	2.5	3.5	4.8	6.0	7.5
3c	75	0.1	0.5	0.8	1.5	5.5	9.3	11.4	13.0
3c	75	2.0	0.5	1.5	2.5	6.5	9.3	11.4	13.0
3c	25	0.1	0.5	0.8	1.0	3.5	4.8	6.0	7.5
3c	25	2.0	0.5	1.8	2.0	4.5	5.5	6.0	7.5

Table B-3
Pressure Increment in the Zion Containment at Vessel Breach

<u>Melt Hole</u>			<u>Cumulative Probabilities</u>						
<u>Case</u>	<u>Melt Mass (%)</u>	<u>Hole Area (M^2)</u>	<u>.1%</u>	<u>1%</u>	<u>5%</u>	<u>50%</u>	<u>95%</u>	<u>99%</u>	<u>99.9%</u>
<u>Pressure Increment (bar)</u>									
4	75	0.1	0.1	0.5	1.0	2.0	3.0	3.5	4.0
4	75	2.0	0.1	1.0	1.5	2.5	3.0	3.5	4.0
4	25	0.1	0.1	0.2	0.3	0.7	1.0	1.2	1.3
4	25	2.0	0.1	0.3	0.5	0.8	1.0	1.2	1.3

Sources of Uncertainty

Expert B was certain that the molten debris is expelled from the cavity as particles or droplets, not as waves or films. Particle size and residence time in the containment atmosphere are uncertain, and were considered; however, in the 1000 to 2000 psi RCS pressure cases, the particle size will probably be of the order of a half of a millimeter, and even for short residence times, the chemical reaction rate is high. Freezing of melt on the reactor cavity walls is highly unlikely, but consideration of such affects the assessment distribution. The rates of mixing, entrainment, and the extent of steam starvation are uncertain and affect the extent of hydrogen production.

Expert C's Elicitation

Issue 7: Pressure Rise at Vessel Breach for Zion

Description of Expert C's Rationale/Methodology

Expert C concluded that it was impossible to duplicate the codes by hand, or even generate good approximations, so his approach was to take the available code calculations, consider the assumptions made in the code itself and the assumptions made in the input for the available code calculations, and then adapt and adjust the results from the codes to get the values required here. He concluded that the code developers and analysts were knowledgeable in the complex physical issues and that they had exercised due diligence in the development and use of the codes. He believed that his role in the elicitation was best served by an interpretation of the codes and available results for the cases at hand. It is impossible to account for all the nonlinearities and interactions in one's head for a problem as complex as this; we rely on the code to do this. A simple approach based on a few hand calculations is too risky for such a complex problem.

Expert C relied primarily on MAAP^{C-1} and CONTAIN^{C-2} calculations. He also utilized the Argonne experiments.^{C-3}

Expert C provided pressure rises for eight subcases for each of the cases defined above. These subcases are defined by a three-letter code:

<u>Position</u>	<u>Description</u>	<u>Letter</u>	<u>Word</u>	<u>Nominal</u>	<u>Range</u>
First	In-vessel zirconium oxidation	H	High	60%	40-80%
		L	Low	25%	10-40%
Second	Vessel hole size	R	Rip	2 m ²	>0.5 m ²
		J	Jet	.1 m ²	<0.5 m ²
Third	Core fraction ejected	M	Major	75%	>50%
		S	Small	33%	<50%

Case Z3b-HJM is Case Z3b as defined above, with High oxidation of zirconium in-vessel, a small (Jet) hole size, and a large (Major) fraction of the core ejected.

Expert C tabulated the number of available code results for each case and subcase. There were available about a dozen calculations each for Z1b-HJM and Z3b-HJM, and two results (each) for Z1b-HJS and Z3b-HJS. The other cases have no code calculations available. Z1b is the worst case, i.e., it gives the highest A_p in containment, so Expert C started with Z1b-HJM. Results for the 44 subcases for which there are no runs at all have to be obtained by shifting and scaling from the four cases for which code results are available.

Expert C thought that the uncertainty in the models in the codes and the input in the codes is adequately represented by the differences between CONTAIN and MAAP. CONTAIN is pessimistic in that all the debris ejected comes out early and then is entrained by the very high velocity gas jet that follows. Furthermore, the trapping assumed in CONTAIN is less efficient than that in MAAP and that shown in the Argonne experiments. Expert C believed that the CONTAIN calculations represent the pessimistic extreme because the pressure rises. He concluded that the code developers and analysts were knowledgeable in the complex physical issues and that they had exercised due diligence in the development and use of the codes. He believed that his role in the elicitation was best served by an interpretation of the codes and available results for the cases at hand. CONTAIN models DCH much better than MAAP does, but some of the assumptions like 100% entrainment are not realistic and not suitable for a best estimate.

Results of Expert C's Elicitation

Expert C provided the following table which contains his conclusions about the pressure rise at vessel breach for Zion. The nomenclature for the various cases has been defined above. All pressure rises are in bars. The three values given are the 1, 50 and 99% values for a cumulative probability curve.

<u>Case</u>	<u>1%</u>	<u>50%</u>	<u>99%</u>	<u>Case</u>	<u>1%</u>	<u>50%</u>	<u>99%</u>
Z1 -HRM	1.0	6.5	9.0	Z1 -LRM	1.0	5.5	8.0
Z1 -HRS	1.0	5.0	7.0	Z1 -LRS	1.0	4.0	6.0
Z1 -HJM	1.0	5.5	8.0	Z1 -LJM	1.0	4.5	7.0
Z1 -HJS	1.0	4.0	6.0	Z1 -LJS	1.0	3.0	5.0
Z1b-HRM	2.0	7.0	10.	Z1b-LRM	2.0	6.0	9.0
Z1b-HRS	2.0	5.5	8.0	Z1b-LRS	2.0	4.5	7.0
Z1b-HJM	2.0	6.0	9.0	Z1b-LJM	2.0	5.0	8.0
Z1b-HJS	2.0	4.5	7.0	Z1b-LJS	2.0	3.5	6.0
Z3 -HRM	1.0	4.5	7.0	Z3 -LRM	1.0	3.5	6.0
Z3 -HRS	1.0	3.0	5.5	Z3 -LRS	1.0	2.5	4.5
Z3 -HJM	1.0	4.0	6.5	Z3 -LJM	1.0	3.0	5.5
Z3 -HJS	1.0	2.5	5.0	Z3 -LJS	1.0	2.0	4.0
Z3b-HRM	2.0	5.0	8.0	Z3b-LRM	2.0	4.0	7.0
Z3b-HRS	2.0	3.5	6.5	Z3b-LRS	2.0	3.0	5.5
Z3b-HJM	2.0	4.5	7.5	Z3b-LJM	2.0	3.5	6.5
Z3b-HJS	2.0	3.0	6.0	Z3b-LJS	2.0	2.5	5.0
Z4 -HSp	2.0	3.0	4.0	Z4 -LSp	1.0	1.5	2.0
Z4 -H	2.0	2.5	3.0	Z4 -L	1.0	1.5	2.0

Expert C concluded that the Z1b values applied to Case Z1a, so a separate set of values for Z1a is not provided. Expert C also decided that the Z3b values applied to Cases Z3a and Z3c as well, so separate values for these cases are not provided. For Case Z4, Expert C thought that the pressure rise would be so small that the Zion containment would not be challenged. He thought that only the amount of zirconium oxidation in-vessel and whether the sprays were operating were important. The first line for the Z4 case above is with the sprays operating (Z4-HSp and Z4-Lsp) and the second line is without the sprays operating.

Expert C provided detailed reasoning for his values for the HJM and HJS subcases for Cases Z1b and Z3b. The other subcases and other cases were treated by analogy and his reasoning is not presented in as much detail. The subcases are discussed in the order in which Expert C considered them since he reasoned from the best known cases and subcases to the less well known.

Case Z1b-HJM: 2500 psia in the RCS at vessel failure, a dry cavity, and no sprays. The HJM subcase is High zirconium oxidation, small (0.5 m^2) hole (Jet), and Major (75%) fraction of the core ejected. This is the worst of the eight subcases except for HRM (R = Rip = large (2 m^2) hole). Expert C thought MAAP Cases 2 and 3, and CONTAIN cases A-6 and A-7, had the most reasonable assumptions. Some of the CONTAIN cases were considered less reasonable because they used an ejection model other than Model A or C. Weighting the two MAAP results equally with the two CONTAIN results, Expert C got six bars for his median or best estimate value for the pressure rise at vessel breach for Zion for subcase Z1b-HJM.

Expert C got the upper bound from CONTAIN runs since he thought they were more pessimistic than the MAAP runs. The worst combination would be the co-entrained water assumption from CONTAIN Case A12 combined with ejection model B from Case A-2. This unlikely combination should give the highest possible Δp ; it is unlikely because co-entrained water implies the steam comes out simultaneously with the debris while ejection model B assumes the debris comes out before the steam. There was no CONTAIN run with this combination, but Expert C estimated that, if run, it would have given a pressure rise of about 9 bars. This gives him the 99% value for this subcase.

The lower bound on the Δp distribution is fixed by the steam spike. For the lower bound, Expert C assumed that there was no hydrogen burn (either never ignited or all pre-existing hydrogen consumed in small burns before breach) and the pressure rise is due to the steam spike alone. This gives 1 or 2 bars; the exact number isn't important given the failure pressure of the Zion containment. There is no need to accurately define the lower tail of the curve since it has no risk significance.

Case Z1b-HJS: 2500 psia in the RCS at vessel failure, a dry cavity, and no sprays. The HJS subcase is High zirconium oxidation; small (0.5 m^2) hole (Jet); and Small (33%) fraction of the core ejected. This subcase is not as severe as HJM because a small rather than a large fraction of the core is involved. Expert C obtained his midpoint pressure rise of 4.5 bar by scaling down from CONTAIN cases A-9 and A-10. CONTAIN Case A-1 was the

similar case for Z1b-HJM, and it was about 1 bar above the Expert C's midpoint value. He thus reasoned that the midpoint for Z1b-HJS should be 4.3 bar. Expert C would expect MAAP runs to give about 3 bars. As 0.5 bar increments are as small as is reasonable to use, Expert C rounded up to 4.5 bars. The upper bound was obtained by scaling down from Z1b-HJM. The lower bound is fixed by the steam spike.

Case Z3b-HJM: 500 to 1000 psia in the RCS at vessel failure, dry cavity, and no sprays. The HJM subcase is High zirconium oxidation; small (0.5 m²) hole (Jet); and Major (75%) fraction of the core ejected. There are no MAAP results available. Expert C assumed they would be about 2 bars below the pressure rises shown for CONTAIN cases B-6 and B-7, so he subtracted a bar from these results, rounded up, and got 4.5 bar for his best estimate or midpoint. He scaled the 99% value down by 1.5 bars from Z1b-HJM since the midpoint dropped by that much. The lower bound is not adjusted since it represents the pressure rise from the steam spike only.

Case Z3b-HJS: 500 to 1000 psia in the RCS at vessel failure, dry cavity, and no sprays. The HJS subcase is High zirconium oxidation; small (0.5 m²) hole (Jet); and Small (75%) fraction of the core ejected. There are no MAAP results available, but Expert C assumed they would be about 2 bars below the pressure rises shown for CONTAIN cases B-9 and B-10. So he subtracted a bar from the CONTAIN results, rounded down, and got 3.0 bar for his best estimate or midpoint. He scaled the 99% value down by 1.5 bars from Z3b-HJM since the midpoint dropped by that much. The lower bound remains fixed.

Z4 Cases: Less than 200 psia in the RCS at vessel failure. Expert C concluded that for these low pressures in the RCS at failure, the effects of hole size and fraction of the core involved were negligible. However, he felt that effects of the sprays were important since they determined the effectiveness of the steam spike. He thus provided pressure rises for the four cases in the table above. Even the highest credible pressure rise for low RCS pressure at breach is so low that the Zion containment is not threatened, so the values shown are not worth spending any more time on even though they are fairly approximate. Expert C estimated the Case Z4 pressure rises from hydrogen burn results for the Seabrook PRA.^{C-3} Seabrook and Zion are enough alike that this is well within the bounds of accuracy needed here. For the worst subcase, high in-vessel zirconium oxidation with sprays, Expert C obtained his upper bound by assuming that there would be 80% zirconium oxidation and he got a resultant pressure of 80 psia, which gives pressure rise of about 4 bars. The other subcases were scaled from this result with the aid of the Seabrook results. The major uncertainty was whether the steam concentration in the containment with no sprays operating would be so high as to preclude hydrogen combustion.

Cases Z1b-HRM and Z1b-HRS: 2500 psia in the RCS at vessel failure, dry cavity, and no sprays. The HRS subcase is High zirconium oxidation; large (2.0 m²) hole (Rlp); and small (33%) fraction of the core ejected. The HRM subcase is similar but has a Major portion of the core ejected. The larger hole will increase the pressure rise at vessel breach somewhat, but not by great amounts in the opinion of Expert C. He scaled the midpoint values and the 99% values up 1 bar from the Z1b-HJM and Z1b-HJS subcase values.

The 1% values stay the same since the steam spike is unaffected by the hole size.

Cases Z1b-LRM, Z1b-LRS, Z1b-LJM and Z1b-LJS: 2500 psia in the RCS at vessel failure, dry cavity, and no sprays. The subcases all have a Low fraction of the zirconium oxidized in-vessel. The zirconium not oxidized in-vessel will oxidize during the HPME if the particle size is small and steam is available. However, the particles may be large enough so that not all the zirconium in them will oxidize, and some particles are bound to be this large even if the bulk of them are not.

Furthermore, sufficient steam may not be available, so the net effect is that the Lxx subcases will have lower pressure rises than the Hxx subcases. Considering the effects of hole size and fraction ejected in the Hxx set of subcases, Expert C reduced both the midpoint and 99% values of the Hxx subcase pressure rises 1.0 bar to obtain the Lxx subcase values. The lower bound stays the same as the steam spike is not affected.

Cases Z3b-LRM, Z3b-LRS, Z3b-LJM and Z3b-LJS: 500 to 1000 psia in the RCS at vessel failure, dry cavity, and no sprays. The subcases all have a Low fraction of the zirconium oxidized in-vessel. These cases were treated by analogy with the Z1b-Lxx cases. Expert C first subtracted 1.0 bar from all the Z3b-Hxx midpoint and 99% values to get the Z3b-Lxx midpoint and 99% values. Since hole size doesn't make as big a difference at these lower pressures, he then added 0.5 bar to the midpoint pressures for subcases LRS and LJS so that the differences between LRM and LJM, and between LRS and LJS would only be 0.5 bar.

Z1a and Z3a Cases: Expert C concluded that the pressure rise for a partially full cavity would be close to that for a dry cavity. He felt they were very unlikely to occur in any event, and that they were more likely to result in pressure rises similar to the dry cases (Z1b and Z3b) than to the full cavity cases (Z1 and Z3).

Z1 Cases: 2500 psia in the RCS at vessel failure, full cavity, and sprays. The problem here is to go from the dry cavity--no sprays cases (Z1b) where we have code results, to the full cavity--sprays cases (Z1) where there are no code results at all. Expert C thought that the water in the cavity was likely to be pushed out of the cavity altogether by the initial jet of debris penetrating the water and impinging on the cavity floor. This water pushed out into the cavity could reduce the pressure rise. FT sees three possible additional effects:

1. The steam produced by the initial jet impingement could efficiently sweep the debris out of the cavity;
2. The steam could enhance the metal-water reaction; and
3. The water droplets in the containment resulting from the sweep-out could quench the small particles entrained in the gas jet which follows the debris ejection.

Expert C saw competing effects from the cavity water and sprays together: the cavity water alone could increase the pressure rise by as much as 1.5 bars, but the sprays alone could reduce the pressure rise by a greater amount. Taking both effects into account, Expert C obtained his Z1 pressure rise values by reducing the Z1b midpoint pressure for each subcase by 0.5 bars, and reducing the 99% pressures by 1.0 bars. The lower bound was reduced to 1.0 bar since the sprays will be very effective in reducing the steam spike.

Z3 Cases: 500 to 1000 psia in the RCS at vessel failure, full cavity, and sprays. Expert C applied the same reasoning to the Z3 cases as he did to the Z1 cases just discussed. He obtained the Z3 subcase values for the midpoints by subtracting 0.5 bars from the equivalent Z3b subcase, and he got the 99% values by subtracting 1.0 bar from the equivalent Z3b subcase.

Z3c Cases: 500 to 1000 psia in the RCS at vessel failure, full cavity, and no sprays. Expert C thought that the increased hydrogen production due to the steam from the full cavity would just about cancel out the cooling effects of the dispersed water at these temperatures. Thus he felt the Z3b pressure rises should apply to all the Z3c subcases.

Sources of Uncertainty

Expert C felt the uncertainty in rates was not particularly important since most processes went to completion. The variability in the fraction ejected and the hole size have partially been accounted for in the subcase structure. The major uncertainties that cause the broadness of the distributions are the amount of zirconium segregation before breach (or the metal fraction ejected early) and the effective particle size. The effect of incomplete hydrogen combustion is small since it is expected to be very nearly complete in all cases.

Correlations with Other Variables

The amount of unoxidized zirconium in the core debris ejected before the gas blowdown should be correlated with the results of the In-Vessel Panel.

Suggested Methods for Reducing Uncertainty

Expert C noted that there were code calculations for only 4 of the 48 cases and subcases. The obvious way to reduce uncertainty is to provide code calculations for the other 44 cases and subcases. This would considerably reduce the error introduced by shifting and scaling the results from the four cases with calculations to cover the other 44 cases. CONTAIN results with the A-6 assumptions for cases Z1, Z1c, Z3, etc. would have been particularly helpful.

References

- C-1. K. Fleming et al., "Risk Management Actions ... Seabrook," Pickard, Lowe, and Garrick, PLG-0550, July 1987.
- C-2. B. W. Spenser et al., "Hydrodynamics and Heat Transfer Aspects of Corium Water Interactions," Electric Power Research Institute, EPRI NP-5127, March 1987.
- C-3. Pickard, Lowe and Garrick, Inc., "Seabrook Station Probabilistic Safety Analysis," prepared for the Public Service Company of New Hampshire and the Yankee Atomic Electric Company, PLG-0300, December 1983.

Expert D's Elicitation

Issue 7: Pressure Rise at Vessel Breach

Description of Expert D's Rationale/Methodology

Expert D performed a thermodynamic calculation for the assessment. The calculation was executed by a computer program that provided the values for the distribution extremes (1 and 99 percentiles). Internal energy tables were employed in the code execution. An adiabatic energy balance was utilized so the effect of hole size was not provided, although it was judged that the distribution ranges would incorporate the effect.

Various assumptions were made for the calculation. It was assumed that the core debris is at 2530 K: 0.257 MJ/kg latent heat and 0.943 MJ/kg sensible heat. Between 0 to 20% (depending on the case being assessed) of the ejected core is quenched, producing steam. From results of Surtsey Tests 2, 3, and 4, it was assumed that at least 10% of the ejected core is frozen on the cavity walls. Both zirconium and iron are reacted with steam in creating hydrogen. When hydrogen is produced, 90% of the hydrogen is burned, and the resulting pressure rise computed (10% is unavailable due to poor mixing in the lower part of containment where air has been purged by steam blowdown).

Expert D believes that detonations will not occur because unconditional burning of hydrogen together with the rate of hydrogen production and mode of mixing precludes detonable mixtures. As an informal check, the results of the calculations were compared with Expert C's preliminary CONTAIN results for Zion and noted that for the upper limits, the results were in general agreement.

Expert D did bounding calculations for the upper and lower bounds of the distributions (1 and 99% percentiles) by setting credible limits on the metal-steam reactions. The extent of the ex-vessel reaction was then varied to complete the distribution. To establish the lower bound of the distribution, 25% metal/steam reaction was assumed, and to establish the upper bound, complete reaction was assumed. In all the distributions, Expert D tended to give a little more weight to the lower values, because the calculation did not include the heat sinks in containment, which, if included would result in a smaller pressure increment.

For shifting from Case 1 and its subcases to Case 3 and its subcases, Expert D varied the amount of quenching depending on the amount of cavity water. In Case 3, it was assumed that there was less steam blowdown energy than Case 1, because there is less water inventory and less energy in the primary system at vessel breach. For Case 4, a steam spike was calculated, negligible hydrogen was produced, and no pressure increment from hydrogen burns was computed. The upper bound for Case 4 was determined by assuming complete conversion of core melt energy to steam.

Results of Expert D's Elicitation

Expert D provided information based on the sensitivity variables of fraction of core ejected (33% and 75%), and extent of in-vessel zirconium reaction (25% and 60%). The distributions for the pressure increment in the Zion containment at vessel breach for Case 1 are provided in Table D-1, for Case 3 in Table D-2, and for Case 4 in Table D-3.

Table D-1
Pressure Increment in the Zion Containment at Vessel Breach

Case	Melt Mass (%)	In-Vessel Zr-reacted (%)	<u>Cumulative Probabilities</u>				
			<u>1%</u>	<u>5%</u>	<u>50%</u>	<u>95%</u>	<u>99%</u>
			<u>Pressure Increment (bar)</u>				
1	33	25	3.0	3.7	4.5	5.3	6.0
1	33	60	3.0	3.6	4.3	4.9	5.5
1	75	25	5.5	6.2	7.0	7.7	8.5
1	75	60	5.0	5.7	6.5	7.2	8.0
1a	33	25	3.5	4.2	5.0	5.8	6.5
1a	33	60	3.0	3.6	4.5	5.2	6.0
1a	75	25	5.8	6.7	7.5	8.4	9.2
1a	75	60	6.0	6.6	7.2	7.8	8.4
1b	33	25	4.0	4.8	5.5	6.2	7.0
1b	33	60	3.5	4.2	5.0	5.8	6.5
1b	75	25	6.1	7.0	7.9	8.8	9.7
1b	75	60	6.4	7.1	7.7	8.3	8.9

Table D-2
Pressure Increment in the Zion Containment at Vessel Breach

Case	Melt Mass (%)	In-Vessel Zr-reacted (%)	Cumulative Probabilities				
			1%	5%	50%	95%	99%
			Pressure Increment (bar)				
3	33	25	2.5	3.2	4.0	4.8	5.5
3	33	60	2.5	3.1	3.8	4.4	5.0
3	75	25	5.0	5.7	6.5	7.2	8.0
3	75	60	4.5	5.2	6.0	6.7	7.5
3a	33	25	3.0	3.7	4.5	5.3	6.0
3a	33	60	2.5	3.1	4.0	4.7	5.5
3a	75	25	5.3	6.2	7.0	7.9	8.7
3a	75	60	5.5	6.1	6.7	7.3	7.9
3b	33	25	3.5	4.3	5.0	5.7	6.5
3b	33	60	3.0	3.7	4.5	5.3	6.0
3b	75	25	5.6	6.5	7.4	8.3	9.2
3b	75	60	5.9	6.6	7.2	7.8	8.4
3c	33	25	3.0	3.7	4.5	5.3	6.0
3c	33	60	3.0	3.6	4.3	4.9	5.5
3c	75	25	5.5	6.2	7.0	7.7	8.5
3c	75	60	5.0	5.7	6.5	7.2	8.0

Table D-3
Pressure Increment in the Zion Containment at Vessel Breach

Case	Melt Mass (%)	In-Vessel Zr-reacted (%)	Cumulative Probabilities				
			1%	5%	50%	95%	99%
			Pressure Increment (bar)				
4	33	25	0.5	0.8	1.2	1.6	2.0
4	33	60	0.5	0.8	1.2	1.6	2.0
4	75	25	0.5	0.8	1.2	1.6	2.0
4	75	60	0.5	0.8	1.2	1.6	2.0

The distributions for the amount of hydrogen produced at vessel breach are provided in Table D-4 for Cases 1 and 3 (H_2 in Case 4 is negligible).

Table D-4
Pressure Increment in the Zion Containment at Vessel Breach

Case	Melt Mass (%)	In-Vessel Zr-reacted (%)	<u>Cumulative Probabilities</u>				
			<u>1%</u>	<u>5%</u>	<u>50%</u>	<u>95%</u>	<u>99%</u>
			<u>Hydrogen Produced (Mg-moles)</u>				
1, 3, 3c	33	25	0.03	0.05	0.08	0.11	0.14
1, 3, 3c	33	60	0.03	0.05	0.07	0.09	0.11
1, 3, 3c	75	25	0.07	0.14	0.20	0.27	0.33
1, 3, 3c	75	60	0.06	0.11	0.16	0.21	0.26
1a, 3a	33	25	0.04	0.08	0.11	0.14	0.17
1a, 3a	33	60	0.07	0.08	0.10	0.12	0.13
1a, 3a	75	25	0.09	0.16	0.24	0.31	0.38
1a, 3a	75	60	0.06	0.11	0.16	0.21	0.26
1b, 3b	33	25	0.05	0.08	0.12	0.16	0.19
1b, 3b	33	60	0.04	0.06	0.09	0.12	0.14
1b, 3b	75	25	0.11	0.19	0.26	0.34	0.42
1b, 3b	75	60	0.08	0.15	0.21	0.27	0.33

Sources of Uncertainty

The main uncertainty identified by Expert D is the extent of gas/debris co-entrainment during debris quenching in the cavity and thus, the extent of the metal-steam reaction; uncertainty in particle size and dispersal is also related. Other uncertainties include the amount of debris quenching, the extent of debris hold-up in the cavity, effects of sprays, mixing in containment, extent of hydrogen burn, and the reactor vessel hole size and mode of steam-debris blowdown. It was judged that the distribution limits provided encompass all these uncertainty effects.

Suggested Methods for Reducing Uncertainty

None.

Expert E's Elicitation

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Description of Expert E's Rationale/Methodology

Expert E concluded that the DCH following vessel failure with the vessel at 1000 psia would be significantly different from the DCH following breach at 500 psia. Therefore he broke up the Z3 cases into Z3 cases (1000 psia) and Z5 (500 psia) cases. Expert E concluded that the pressure rise for Case Z3c would not differ significantly from that for Case Z3, so separate pressure rise values for Case Z3c are not given.

Expert E also decided that he could not make meaningful distinctions based on the metallic content of the ejected core material, so he eliminated the fraction of the zirconium oxidized in-vessel as a variable. His subcase structure is defined by a two-letter code:

<u>Position</u>	<u>Description</u>	<u>Letter</u>	<u>Word</u>	<u>Nominal</u>	<u>Range</u>
First	Core Fraction Ejected	C	Large	75%	> 50%
		c	Small	33%	< 50%
Second	Vessel Hole Size	H	Large	π^2	> 0.5 m ²
		h	Small	π^2	< 0.5 m ²

That is, Case Z3b-Ch is vessel failure at 1000 psia, dry cavity, no sprays, a large fraction of the core ejected, and a small initial hole size (penetration failure).

Expert E relied primarily on MAAP^{E-1} and CONTAIN^{*} calculations. Results of code calculations are available only for Z1b-Ch, Z1b-ch, Z3b-Ch, and Z3b-ch. Most of the results available are for the Ch subcase for both Case Z1b and Z3b. Therefore, Expert E considered his "base" subcase to be Ch: large fraction of the core ejected and small hole.

Expert E also considered calculations performed by a member of the Source Term Panel concerning fission product release during DCH. In that Expert's model, only about 20% of the core debris could be finely fragmented and thus contribute to DCH upon dispersal from the reactor cavity. This is in contrast to the available MAAP and CONTAIN calculations which assume that 75 to 100% of the core may be fragmented and dispersed. Hence, the maximum pressure attainable in a DCH event is substantially lower in this new model than in the MAAP and CONTAIN calculations. There is uncertainty in the fraction of debris which can participate in DCH, but the available code calculations for Zion were performed with large fractions rather than with a range of values.

^{*}T. Ginsberg, Letter, "Brookhaven CONTAIN Calculations," March 1986

Expert E obtained his midpoint values for Z1b-Ch and Z3b-Ch by weighting the CONTAIN results more or less equally with the MAAP results with UCHB. To obtain his upper bound, he considered the CONTAIN results and physical limitations. He noted that only with very conservative assumptions did the CONTAIN analyses attain maximum pressures over 10 bars. The maximum found with the MAAP code was around 7 bars. The lower bound of his distribution for pressure rise is fixed by a steam spike with no hydrogen burn, which results in a 1.0 to 2.0 bar pressure rise "floor" for all the distributions. Expert E chose his midpoint pressure rise to be closer to the lower bound than to the upper bound. This reflects his belief that, while there may be broad uncertainty, the probability of approaching the upper bound is small.

The pressure rise distributions for all the other cases and subcases were determined from these base cases by shifting the results of the base cases, scaling the results of the base cases, or both. In applying a shift to the base case, a value was added to the midpoint and upper bound values. In scaling the base case values, the difference between the midpoint value or the upper bound and the lower bound was multiplied by a factor. The lower bound value is usually not affected by these operations since it is fixed by the pressure rise attributable to the steam spike alone. This pressure rise is not affected by the phenomena being accounted for in the shifting and scaling adjustments. If both adjustments are applied, the shifting adjustment is applied first.

In going from the dry cavity cases where there were code runs available to the wet cavity cases where there were no code results, Expert E concluded that the upper bound was not affected since it is possible that the water in the cavity might all be expelled from it before the DCH portion of the event commenced. Based on Spenser's experiments,^{E-2} he considered it more likely that some quenching would occur, however, and the midpoint value for the wet cavity case was reduced 1.0 to 2.0 bars below the value for the equivalent dry cavity case. For the partially-full cavity cases, Expert E considered that water expulsion was more likely than in the full cavity case. The midpoint pressure rise values for these cases are 0.5 to 1.0 bars below the value for the equivalent dry cavity case.

Expert E also considered the co-entrainment of water and debris which is part of the DCH model in CONTAIN.^{E-3} He discounted this effect for two reasons. First, the co-entrainment caused a slight increase in pressure in the Surry results and a slight decrease in pressure in the Bellefonte results. Second, the increased pressure rise in the Surry results was noted for cavity water masses less than 70 MT and attained its maximum when the cavity water mass was 30 MT. However, when half full the Zion cavity holds about 100 MT of water, so if even half that amount of water were co-entrained, the hypothetical pressure rise would be small.

Results of Expert E's Elicitation

Expert E provided the following table which contains his conclusions about the pressure rise at vessel breach for Zion. The nomenclature for the various cases has been defined above. All pressure rises are in bars. The three values given are the 1, 50 and 99% values for a cumulative probability curve.

<u>Case</u>	<u>1%</u>	<u>50%</u>	<u>99%</u>	<u>Case</u>	<u>1%</u>	<u>50%</u>	<u>99%</u>
Z1-Ch	2.0	4.0	8.0	Z1 -ch	2.0	3.0	5.0
Z1-CH	2.0	5.5	10.0	Z1 -cH	2.0	3.5	6.0
Z1a-Ch	2.0	4.0	8.0	Z1a-ch	2.0	3.0	5.0
Z1a-CH	2.0	6.0	10.0	Z1a-cH	2.0	4.0	6.0
Z1b-Ch	2.0	5.0	8.0	Z1b-ch	1.0	3.0	5.5
Z1b-CH	2.0	7.5	10.0	Z1b-cH	2.0	4.5	6.5
Z3-Ch	2.0	3.5	6.0	Z3 -ch	2.0	3.0	5.0
Z3-CH	2.0	4.0	7.5	Z3 -cH	2.0	3.5	5.5
Z3a-Ch	2.0	3.5	6.0	Z3a-ch	2.0	3.0	5.0
Z3a-CH	2.0	4.5	7.5	Z3a-cH	2.0	3.5	5.5
Z3b-Ch	2.0	4.5	6.0	Z3b-ch	1.0	3.5	5.0
Z3b-CH	2.0	6.0	8.0	Z3b-cH	1.0	4.0	6.0
Z4-Ch	2.0	3.0	4.0	Z4 -ch	2.0	2.5	3.0
Z4-CH	2.0	3.0	4.0	Z4 -cH	2.0	2.5	3.0
Z5b-Ch	2.0	3.5	5.0	Z5b-ch	1.0	3.0	5.0
Z5b-CH	2.0	5.0	7.0	Z5b-cH	2.0	4.0	6.0

Expert E concluded that the Z5b values applied to Cases Z5 and Z5a, so no distributions are shown for Cases Z5 and Z5a.

A case-by-case discussion follows. The cases and subcases are presented in the order Expert E considered them as he reasoned from the cases for which the most information was available to the cases for which the least information was available.

Case Z1b: 2500 psia in the RCS at vessel failure, a dry cavity, and no sprays. For subcase Ch, Expert E based his midpoint value on CONTAIN Case A-2 ($\Delta p = 6.6$ bars) and MAAP with UCHB ($\Delta p = 4.0$ bars). The MAAP result assumed a lower metallic content than given here, and so is adjusted upward about 1.0 bar. The upper bound for Z1b-Ch is based on CONTAIN Cases A-2 and A-3 ($\Delta p = 8.0$ bars); the lower bound is based on MAAP with no burn ($\Delta p = 2.5$ bars). For subcase CH, the available sensitivity studies indicated that the shift value should be about +1.0 bar, and the scale factor should be about 1.33. This makes the subcase CH midpoint value about 2.5 bars higher than the subcase Ch midpoint value. The upper bound does not rise

quite this much because of physical limitations on the possible pressure rise. In going from the Cx subcases to the cx subcases, the shift value was -1.0 bar and the scale factor was 0.75, based on CONTAIN Case A-10. The midpoint value for subcase ch is thus 2.0 bars below that for subcase Ch. The reduction in the amount of the core involved in DCH does not reduce the pressure rise proportionately since a large portion of the pressure rise is due to hydrogen combustion, which does not depend on the fraction of the core ejected.

Case Z1: 2500 psia in the RCS at vessel failure, a full cavity, and sprays. For subcase Ch, Expert E used the results of Spencer's experiments³ to reduce the Z1b-Ch midpoint value 1.0 bar to get the midpoint value for Z1-Ch. This accounts for quenching. The CONTAIN sensitivity analyses for Surry and Sequoyah support this effect of a full cavity. The upper bound for Z1-Ch remains the same as for Z1b-Ch since the water in the cavity may be expelled early in the event and there will be no net lowering of the pressure rise. The lower bound is fixed by the steam spike alone. For subcase CH, the Z1-Ch values are adjusted with a scale factor of 1.33. In going from the Cx subcases to the cx subcases, a scale factor of 0.5 was used.

Case Z1a: 2500 psia in the RCS at vessel failure, a partially full cavity, and no sprays. Expert E thought that the four subcases for Case Z1a would be similar to those for Case Z1. Pressure rise for the ch and Ch cases were taken to be the same as in the full cavity (Z1) cases, while the median pressure rises for the cH and CH cases were adjusted upward from the Z1 cases to account for less quenching or water expulsion.

Case Z3b: 1000 psia in the RCS at vessel failure, dry cavity, and no sprays. For subcase Ch, Expert E based his midpoint value on CONTAIN Case B-7 ($\Delta p = 5.7$ bars) and MAAP with UCHR ($\Delta p = 4.0$ bars). The MAAP mechanistic sweepout model predicts complete sweepout which the RCS pressure about 1000 psia before breach, and Expert E agrees with this prediction. The upper bound for Z3b-Ch is based on CONTAIN cases B-2 and B-3 ($\Delta p = 6.3$ bars); the lower bound is based on MAAP with no burn ($\Delta p = 2.5$ bars) but was reduced to 2.0 bars for reasons not given. For subcase CH, the available sensitivity studies indicated that the shift value should be about +1.0 bar, and the scale factor should be about 1.33. This makes the subcase CH midpoint value about 1.5 bars higher than the subcase Ch midpoint value. The upper bound rises by the same amount. In going from the Cx subcases to the cx subcases, the shift value was -0.5 bar and the scale factor was 0.75, based on CONTAIN Case B-10. The midpoint value for subcase ch is thus 1.0 bars below that for subcase Ch. The reduction in the amount of the core involved in DCH does not reduce the pressure rise proportionately since a large portion of the pressure rise is due to hydrogen combustion, which does not depend on the fraction of the core ejected.

Case Z3: 1000 psia in the RCS at vessel failure, a full cavity, and sprays. For subcase Ch, Expert E used the results of Spencer's experiments³ to reduce the Z3b-Ch midpoint value 1.0 bar to get the midpoint value for Z3-Ch. This accounts for quenching and a less effective hydrogen burn. The upper bound for Z3-Ch remains the same as for Z3b-Ch.

The lower bound is fixed by the steam spike alone. For subcase CH, the Z3-CH values are adjusted with a scale factor of 1.33. In going from the Cx subcases to the cx subcases, a scale factor of 0.5 was used.

Case Z3a: 1000 psia in the RCS at vessel failure, a partially full cavity, and no sprays. Expert E thought that the four subcases for Case Z3a would be similar to those for Case Z3. Pressure rises for these cases were taken to be the same as in the full cavity (Z3) cases, except that the median for the CH case was judged to be higher to account for less quenching or water expulsion.

Case Z4: Less than 200 psia in the RCS at vessel failure. The midpoint values are typical for pressure rises resulting from effective quenching. As very little hydrogen is generated, there is little pressure rise attributable to hydrogen combustion.

Cases Z5, Z5a, and Z5b: 500 psia in the RCS at vessel failure. Expert E separated these cases from the Z3 (1000 psia) cases because 500 psia is so close to the threshold of entrainment that the dispersal mechanism may be predominantly wavelike. In the table above, results are shown only for Case Z5b, and these apply to cases Z5 and Z5a. Expert E used CONTAIN Case C-1 ($\Delta p \approx 4.0$ bars) as a basis; he adjusted this result upward somewhat to get his upper bound and downward to get his midpoint value. At this low driving pressure, particle quench in the lower compartment is possible even though there is no water in the cavity. Spencer's experiments indicate that very little difference between full cavity and dry cavity can be expected at these pressures.

Sources of Uncertainty

Expert E had little to say about the sources of uncertainty. The variability in the fraction ejected and the hole size have partially been accounted for in the subcase structure. Uncertainties that cause the breadth of the distributions are the amount of zirconium oxidation before breach (or the metal fraction ejected) and the extent of wavelike vs. particle-like debris form in the lower compartment.

Correlations with Other Variables

Since Expert E did not give separate results for the high and low cases for the amount of unoxidized zirconium in the core debris ejected before the gas blowdown, it will not be possible to correlate his pressure rise values with this factor in the results of the In-Vessel Expert Panel.

Suggested Methods for Reducing Uncertainty

Expert E noted that there were code calculations for very few of the many cases and subcases. The obvious way to reduce uncertainty is to provide code calculations for the cases and subcases for which there are presently no results. This would considerably reduce the errors introduced by shifting and scaling the results from the cases and subcases with code results to cover the other cases and subcases.

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- E-3. D. G. Williams et al., "Containment Loads Due to Direct Containment Heating and Associated Hydrogen Behavior: Analysis and Calculations with the CONTAIN Code," Sandia National Laboratories, NUREG/CR-4896, SAND87-0633, May 1987.

6. MOLTEN CORE/CONTAINMENT INTERACTION ISSUES RESULTS--Part 2

The results in this section deal with Molten Core Containment Interaction Issues (MCCI) issues.

6.1 MCCI Issue 1: Peach Bottom Drywell Shell Meltthrough

Summary and Aggregation of MCCI Issue 1: Peach Bottom Drywell Shell Meltthrough

Experts consulted: Dave Bradley, Sandia National Laboratories; Mike Corradini, University of Wisconsin; George Greene, Brookhaven National Laboratory; Mike Hazzan, Stone & Webster; Mujid Kazimi, Massachusetts Institute of Technology; Raj Sehgal, Electric Power Research Institute.

Issue Description

This issue relates to whether containment failure occurs as a result of core debris contacting the steel drywell shell at the drywell floor level. The reviewers were asked to provide subjective probabilities for drywell failure in this mode for several different boiling water reactor (BWR) vessel breach scenarios. The suggested scenarios were characterized by six parameters. These six parameters and the various levels associated with each parameter are presented in the table below.

The variable elicited was the probability of drywell failure as a function of time.

Suggested Scenario Parameters

<u>Scenario Parameters</u>	<u>Levels</u>
1. Failure Mode	a. Plop (> 40% of core released at vessel breach) b. Penetration failure of vessel
2. RPV Pressure	a. High (1000 psia) b. Low (200 psia)
3. Debris Superheat	a. High (> 100 K) b. Low (< 100 K)

<u>Scenario Parameters</u>	<u>Levels</u>
4. Debris Unoxidized Metal Upon Egress From Vessel	a. High % metal - 65% zirconium equivalent initially in debris on concrete (meant to encompass a range of 50% - 80%) b. Low % Metal - 35% zirconium equivalent initially in debris on concrete (meant to encompass a range of 20 to 50%)
5. Water on Drywell Floor	a. Yes (replenished) b. No (not replenished)
6. Decay Power Level	a. High (soon after scram--2 h) b. Low (well after scram--10 h)

After the discussion the experts decided to consider debris flow rate from the vessel rather than failure mode, and decided that the decay power level did not impact the scenario enough to consider as an additional parameter. The flow rates considered were < 50 kg/s, 50 to 100 kg/s, and > 100 kg/s.

Summary of Experts' Rationale/Methodology

There seemed to be two schools of thought on this issue. Some experts felt that debris spreading is hydrodynamically limited and that the drywell shell will fail almost every time that the vessel is breached. Other experts felt that the movement of the debris is thermodynamically limited and will be impeded by crust formation and the presence of water; these experts felt that the drywell shell will not fail every time the vessel is breached.

All experts agreed that the drywell shell will fail in the range of 1000 to 1300 K. They also agreed that superheat in the early phases of the accident is extremely important and that there always will be enough unoxidized metal in the debris to fuel a vigorous core concrete interaction. The areas of disagreement were the debris spreading limitations (as mentioned in the previous paragraph), the effect of water, and the effect of the CRD materials underneath the reactor pressure vessel.

Expert A based his assessment on a simple heat conduction model. The model accounted for boiling heat transfer in the cases in which water was present and for radiation heat transfer from the shell to the atmosphere above the drywell floor. The expert felt that the debris flow rate from the vessel was extremely important because the flow rate determines the depth of debris on the drywell floor and the heat content of the debris when it reaches the drywell shell. A high debris flow rate will also tend to sweep away crusts that form at the interface between the debris and the drywell shell.

The Expert felt that either the condition of low percentage of unoxidized metal in the debris or the condition of low initial superheat in the debris will favor stable crust formation. Whenever a crust is formed at the shell, the crust will insulate the shell and the probability of shell failure will diminish.

He felt that if water is present on top of the debris, that it will be in the boiling heat transfer regime and will reduce the probability of shell failure. He also felt that the CRD structure underneath the vessel would disperse the flow and remove energy from the debris in high debris flow cases.

Expert B based his assessment on a two-dimensional heat-conduction model of the drywell shell (the model included convection from the debris) and several CORCON calculations. He felt that debris spreading will be controlled by the metallic phase since a small fraction of the initial core debris is oxidic. There will therefore be a rapid initial ablation of the concrete, a high gas release and a high heat source from chemical reactions. (This is consistent with experimental results.) Debris spreading is expected to be hydrodynamically limited, not thermodynamically limited.

The Expert felt that quenching of core debris is unlikely. Water reduces the flow of molten metal as a result of the cooling of the leading edge of the flowing melt. Water will have a significant impact only when the melt superheat is quite low. Expert B felt that crust formation is unlikely in the presence of a flowing core melt under most conditions.

The Expert concluded that drywell shell failure was likely except for cases with shallow debris layers cooled by water and for cases with inefficient heat transfer.

Expert C, from experimental observation, felt melt spreading to be a hydrodynamically limited phenomenon (not limited by heat transfer). He predicted that there will be minimum sump retention due to inertial effects and no floor-mounted obstacles to debris flow. He felt that the melt will contact the steel shell within seconds of RPV failure.

The Expert felt that water will present minimal opposition to melt spreading (melts have been observed to flow under water experimentally). The melt water thermal interactions will be in the film boiling regime, retarding heat transfer; attenuation of core flow will be a secondary effect. The Expert felt that crusts are not expected to appear early.

The Expert concluded that there is a high probability of drywell shell failure.

Expert D felt that in most scenarios, heat removal from the CRD structure underneath the RPV or heat removal from overlaying water pools would allow crusts to form. The Expert felt that the drywell shell failure probability would be low in most cases.

Experts E and F provided information regarding the rationale for their elicitations after the completion of their elicitation write-up. That information is summarized in this section.

Expert E assumed that the entire drywell floor is available for spreading. He assumed that the melt spreads across the drywell floor in an even, quasi-steady manner, without dynamic effects, above its solidus point. As the melt fills the sump region, the activity is high, no crusts are formed (prevented by gas sparging from the core concrete interaction), mixing is expected, and the melt flows quickly. The melt cools quickly as the melt spreads to the drywell wall (from spreading over such a large area.) Crusts begin to form and the radial heat flux is reduced by a factor of 3 to 4.

The Expert felt that the CRD materials underneath the RPV will prevent the lower plenum wall from unzipping. It can act as a mechanical breakup mechanism and as a heat sink. The first two effects could be important, the third may be a second order effect.

The Expert felt that water enhances crusting behavior and potentially prevents melt from spreading. He also stated that crusting occurs when melt is spread out over an extremely wide area.

Expert F assumed a semi-circular progression of the melt into the annular region of the drywell. He performed a heat balance for the semi-circular leading edge to calculate how far the melt reaches before reaching the freezing point. He neglected upward radiation losses because they are smaller than the downward heat loss to concrete. He assumed that the maximum heat generation rate over the height of the melt is limited by the concrete decomposition rate which is limited by the downward heat flux. The heat flux to the decomposing concrete is given by:

$$q'' = 20(T - T_p)^2 \text{ W/m}^2$$

where

T = melt temperature and T_p = decomposition temperature.

The Expert assumed that a stable crust will form at the leading edge. He modeled the drywell shell as an annular fin conducting the heat upward and radiating the heat to the atmosphere above the melt.

Method of Aggregation

Several things were done to the individual elicitations in order to aggregate them: interpolation to complete all of the quantiles necessary to average the elicitations; if no information was given for a variable, it was assumed that it did not impact the scenario; some of the scenarios provided by the experts were averaged together to avoid expanding the table into further dimensions (e.g., FCI, no FCI); and in one case the CDF was created from best estimates of failure times.

Forty-eight cases were averaged

**Complete Set of Scenarios for Consideration
in Aggregation of Peach Bottom Drywell Shell Failure Issue**

A) Low flow rate (<50 kg/s)

A1)	High Pressure,	High % Metal,	High Superheat,	Water
A2)	High Pressure,	High % Metal,	High Superheat,	No Water
A3)	High Pressure,	High % Metal,	Low Superheat,	Water
A4)	High Pressure,	High % Metal,	Low Superheat,	No Water
A5)	High Pressure,	Low % Metal,	High Superheat,	Water
A6)	High Pressure,	Low % Metal,	High Superheat,	No Water
A7)	High Pressure,	Low % Metal,	Low Superheat,	Water
A8)	High Pressure,	Low % Metal,	Low Superheat,	No Water
A9)	Low Pressure,	High % Metal,	High Superheat,	Water
A10)	Low Pressure,	High % Metal,	High Superheat,	No Water
A11)	Low Pressure,	High % Metal,	Low Superheat,	Water
A12)	Low Pressure,	High % Metal,	Low Superheat,	No Water
A13)	Low Pressure,	Low % Metal,	High Superheat,	Water
A14)	Low Pressure,	Low % Metal,	High Superheat,	No Water
A15)	Low Pressure,	Low % Metal,	Low Superheat,	Water
A16)	Low Pressure,	Low % Metal,	Low Superheat,	No Water

B) Medium flow rate (50 kg/s < flow rate < 100 kg/s)

B1)	High Pressure,	High % Metal,	High Superheat,	Water
B2)	High Pressure,	High % Metal,	High Superheat,	No Water
B3)	High Pressure,	High % Metal,	Low Superheat,	Water
B4)	High Pressure,	High % Metal,	Low Superheat,	No Water
B5)	High Pressure,	Low % Metal,	High Superheat,	Water
B6)	High Pressure,	Low % Metal,	High Superheat,	No Water
B7)	High Pressure,	Low % Metal,	Low Superheat,	Water
B8)	High Pressure,	Low % Metal,	Low Superheat,	No Water
B9)	Low Pressure,	High % Metal,	High Superheat,	Water
B10)	Low Pressure,	High % Metal,	High Superheat,	No Water
B11)	Low Pressure,	High % Metal,	Low Superheat,	Water
B12)	Low Pressure,	High % Metal,	Low Superheat,	No Water
B13)	Low Pressure,	Low % Metal,	High Superheat,	Water
B14)	Low Pressure,	Low % Metal,	High Superheat,	No Water
B15)	Low Pressure,	Low % Metal,	Low Superheat,	Water
B16)	Low Pressure,	Low % Metal,	Low Superheat,	No Water

C) High flow rate (>100 kg/s--includes plop and HPME)

C1)	High Pressure,	High % Metal,	High Superheat,	Water
C2)	High Pressure,	High % Metal,	High Superheat,	No Water
C3)	High Pressure,	High % Metal,	Low Superheat,	Water
C4)	High Pressure,	High % Metal,	Low Superheat,	No Water
C5)	High Pressure,	Low % Metal,	High Superheat,	Water
C6)	High Pressure,	Low % Metal,	High Superheat,	No Water
C7)	High Pressure,	Low % Metal,	Low Superheat,	Water
C8)	High Pressure,	Low % Metal,	Low Superheat,	No Water

C9)	Low Pressure,	High % Metal,	High Superheat,	Water
C10)	Low Pressure,	High % Metal,	High Superheat,	No Water
C11)	Low Pressure,	High % Metal,	Low Superheat,	Water
C12)	Low Pressure,	High % Metal,	Low Superheat,	No Water
C13)	Low Pressure,	Low % Metal,	High Superheat,	Water
C14)	Low Pressure,	Low % Metal,	High Superheat,	No Water
C15)	Low Pressure,	Low % Metal,	Low Superheat,	Water
C16)	Low Pressure,	Low % Metal,	Low Superheat,	No Water

Many of the distributions that resulted from averaging the experts' results were very similar. To simplify the APET, an ANOVA analysis (see description of ANOVA in Section 5.6); was performed to reduce the number of cases. Distributions for the following five cases were implemented into the event tree.

- a) Low and medium flow with water
- b) Low and medium flow without water
- c) High flow with water
- d) High flow without water and two out of three other parameters high (pressure, percentage of metal, and superheat)
- e) High flow without water and two out of three other parameters low (pressure, percentage of metal, and superheat)

Aggregated Results

Values in tables are probabilities of drywell shell failure for given case (e.g., A1) and given time. Description of cases are found in the previous section.

Table 6-1
Average of 48 cases
(Average of all six experts--drywell shell failure issue)

<u>Case</u>	<u>2 min</u>	<u>5 min</u>	<u>10 min</u>	<u>1 h</u>	<u>2 h</u>	<u>3 h</u>	<u>5 h</u>	<u>10 h</u>	<u>CCI neg</u>
A1	0.01	0.10	0.23	0.33	0.34	0.34	0.34	0.34	0.34
A2	0.17	0.26	0.39	0.51	0.53	0.55	0.55	0.55	0.55
A3	0.01	0.10	0.23	0.33	0.34	0.34	0.34	0.34	0.34
A4	0.17	0.26	0.38	0.49	0.51	0.51	0.51	0.51	0.51
A5	0.01	0.08	0.22	0.32	0.33	0.33	0.34	0.34	0.34
A6	0.17	0.24	0.38	0.49	0.51	0.53	0.53	0.53	0.53
A7	0.01	0.08	0.22	0.32	0.33	0.33	0.34	0.34	0.34
A8	0.17	0.24	0.38	0.48	0.50	0.51	0.51	0.51	0.51
A9	0.00	0.06	0.18	0.31	0.33	0.33	0.33	0.33	0.33
A10	0.02	0.15	0.35	0.51	0.53	0.55	0.55	0.55	0.55
A11	0.00	0.02	0.12	0.28	0.30	0.32	0.33	0.33	0.33
A12	0.02	0.11	0.28	0.46	0.50	0.51	0.51	0.51	0.51

Table 6.1 (continued)

<u>Case</u>	<u>2 min</u>	<u>5 min</u>	<u>10 min</u>	<u>1 h</u>	<u>2 h</u>	<u>3 h</u>	<u>5 h</u>	<u>10 h</u>	<u>CCI neg</u>
A13	0.00	0.06	0.18	0.31	0.33	0.33	0.33	0.33	0.33
A14	0.02	0.14	0.35	0.50	0.52	0.53	0.53	0.53	0.53
A15	0.00	0.02	0.12	0.28	0.30	0.31	0.32	0.32	0.33
A16	0.02	0.11	0.28	0.46	0.49	0.50	0.51	0.51	0.51
B1	0.01	0.10	0.30	0.35	0.36	0.36	0.36	0.36	0.36
B2	0.17	0.26	0.51	0.60	0.61	0.61	0.62	0.62	0.62
B3	0.01	0.10	0.30	0.34	0.35	0.35	0.35	0.35	0.35
B4	0.17	0.26	0.47	0.52	0.53	0.53	0.53	0.53	0.53
B5	0.01	0.09	0.29	0.36	0.36	0.37	0.38	0.38	0.38
B6	0.17	0.25	0.45	0.54	0.56	0.56	0.57	0.57	0.57
B7	0.01	0.08	0.28	0.32	0.33	0.34	0.34	0.34	0.35
B8	0.17	0.25	0.45	0.50	0.51	0.52	0.52	0.52	0.52
B9	0.00	0.07	0.25	0.33	0.34	0.35	0.35	0.35	0.35
B10	0.02	0.15	0.47	0.60	0.61	0.61	0.62	0.62	0.62
B11	0.00	0.03	0.19	0.29	0.31	0.33	0.34	0.34	0.35
B12	0.02	0.11	0.37	0.49	0.52	0.53	0.53	0.53	0.53
B13	0.00	0.07	0.25	0.35	0.36	0.37	0.37	0.37	0.37
B14	0.02	0.15	0.42	0.55	0.56	0.56	0.57	0.57	0.57
B15	0.00	0.03	0.18	0.28	0.30	0.31	0.32	0.33	0.33
B16	0.02	0.11	0.36	0.48	0.50	0.51	0.52	0.52	0.52
C1	0.02	0.18	0.35	0.41	0.41	0.41	0.41	0.41	0.41
C2	0.21	0.59	0.77	0.84	0.85	0.85	0.85	0.85	0.85
C3	0.02	0.15	0.29	0.35	0.36	0.36	0.36	0.36	0.36
C4	0.21	0.52	0.63	0.78	0.79	0.79	0.79	0.79	0.80
C5	0.02	0.15	0.30	0.36	0.36	0.37	0.37	0.37	0.37
C6	0.21	0.43	0.65	0.71	0.72	0.72	0.73	0.73	0.73
C7	0.02	0.14	0.29	0.35	0.35	0.35	0.35	0.35	0.35
C8	0.21	0.36	0.49	0.56	0.57	0.58	0.58	0.58	0.58
C9	0.05	0.22	0.38	0.44	0.44	0.45	0.46	0.46	0.46
C10	0.21	0.59	0.78	0.85	0.86	0.87	0.87	0.87	0.87
C11	0.05	0.18	0.33	0.39	0.39	0.39	0.39	0.39	0.39
C12	0.21	0.41	0.53	0.66	0.67	0.67	0.68	0.68	0.68
C13	0.05	0.18	0.33	0.39	0.40	0.40	0.40	0.40	0.40
C14	0.21	0.39	0.57	0.63	0.64	0.65	0.65	0.65	0.65
C15	0.05	0.18	0.32	0.38	0.38	0.38	0.38	0.39	0.39
C16	0.21	0.35	0.47	0.53	0.54	0.54	0.54	0.54	0.54

Table 6-2
Average of Five Collapsed Cases After ANOVA
[Values in tables are probabilities of
drywell shell failure and given time]

<u>Average of Low and Medium Flow Cases With Water</u>								
2 min	5 min	10 min	1 h	2 h	3 h	5 h	10 h	CCI neg
0.00	0.07	0.22	0.32	0.33	0.34	0.34	0.34	0.35
<u>Average of Low and Medium Flow Cases Without Water</u>								
2 min	5 min	10 min	1 h	2 h	3 h	5 h	10 h	CCI neg
0.09	0.19	0.39	0.51	0.53	0.54	0.54	0.54	0.54
<u>Average of High Flow Cases With Water (C1, C3, ..., C15)</u>								
2 min	5 min	10 min	1 h	2 h	3 h	5 h	10 h	CCI neg
0.04	0.17	0.32	0.38	0.39	0.39	0.39	0.39	0.39
<u>Average of High Flow Cases, No Water, > 2/3 of Other Parameters High (press. & metal. superheat)</u>								
2 min	5 min	10 min	1 h	2 h	3 h	5 h	10 h	CCI neg
0.21	0.53	0.71	0.79	0.80	0.81	0.81	0.81	0.81
<u>Average of High Flow Cases, No Water, > 2/3 of Other Parameters Low (press. & metal. superheat)</u>								
2 min	5 min	10 min	1 h	2 h	3 h	5 h	10 h	CCI neg
0.21	0.38	0.51	0.60	0.61	0.61	0.61	0.61	0.61

Individual Elicitations for MCCI Issue 1

Expert A's Elicitation

Issue 1: Peach Bottom Drywell Shell Meltthrough

Description of Expert A's Rationale/Methodology

Expert A combined the failure mode parameter with the RPV pressure parameter and expressed the result as a debris flow rate. The Expert considered three debris flow rates: high or "plop" (greater than 100 kg/s); medium (between 50 kg/s and 100 kg/s); and low (less than 50 kg/s). For the "plop" case the Expert assumed the majority of the core was released from the vessel. The Expert believed that the flow rate was important because it determines the debris depth on the drywell floor and the heat content of the debris when it reaches the drywell shell. For cases with a high flow rate the debris will reach the shell more quickly and with a higher heat content than for cases with a low flow rate. In addition, the high flow rate cases will tend to "sweep away" crusts that form on the shell, thus increasing the heat transfer to the shell. Also, higher heat transfer coefficients are generally associated with high debris flow rates than with low debris flow rates.

For the unoxidized metal content in the debris, the Expert considered that the high level corresponded to more than 70% unoxidized metal. The effects of this parameter are that a metal-rich debris composition has the potential to release a lot of chemical energy, and an oxide-rich composition favors a stable crust formation.

A high superheat level was assumed to range from 100 to 1000 K. A low superheat level corresponds to a superheat of less than 100 K. The amount of superheat in the debris "sets" the initial energy content of the debris, drives the heat transfer, and affects the formation of a crust. A low superheat level favors the formation of a stable crust.

The Expert felt that the presence of water in the drywell would cool the shell via boiling heat transfer and, thus, reduce the probability of shell failure.

The Expert believed that the difference between the decay power at 2 h and 10 h would have only a negligible effect, and therefore it was not included as a parameter in his assessment.

The Expert also believed that the presence of a mechanical barrier (e.g., the "Rat's Nest" of steel under the RPV) was important for the high flow-rate case ("plop") because it would tend to remove energy from the debris, disperse the debris jet, and cause the debris to rain into the pool, increasing the likelihood that the debris would be quenched.

The Expert felt that the formation of a stable crust at the shell was very important because the crust would insulate the shell and, thus, reduce the probability of shell failure. Debris material with a low amount of superheat and a high oxide content favored the formation of a crust, whereas cases with a high flow rate discouraged crust formation (swept crust away).

The Expert based his estimates on a simple heat-conduction model. The heat-conduction model accounted for boiling heat transfer (for cases where water was present) and for radiation heat transfer from the shell to the atmosphere above the drywell floor (radiation from the debris to the shell was not modeled, however). This simple model allowed the Expert to vary various model parameters to see their effects on the shell temperature. The Expert's failure criteria were based on an "office" survey he conducted of structural experts which indicated that the drywell shell would lose its strength in the range of 1100 K to 1500 K. In addition, he assumed the melting temperature of the shell was approximately 1750 K. The uncertainty in the temperature at which the drywell shell will fail has been included in his assessment.

Results of Expert A's Elicitation

The Expert assessed the cumulative probability of drywell shell failure for four different times: 10 min, 1 h, 3 h, and when CCI releases are negligible (approximately 10 h). The Expert believed, however, if the drywell is going to fail, it will fail within 3 h. Thus, the probabilities at 3 h and when CCI releases are negligible are the same. The results are presented in Table A-1.

Table A-1
Cumulative Probability of Drywell Shell Failure

<u>Scenario Parameters</u>				<u>Time*</u>			
<u>Pour Rate</u>	<u>Metal</u>	<u>Superheat</u>	<u>Water</u>	<u>10 min</u>	<u>1 h</u>	<u>3 h</u>	<u>CCI Neg</u>
High	Low	Low	Yes	0.002	0.01	0.01	0.01
High	Low	Low	No	0.02	0.1	0.1	0.1
High	Low	High	Yes	0.05	0.05	0.05	0.05
High	Low	High	No	0.2	0.2	0.2	0.2
High	High	Low	Yes	0.002	0.02	0.02	0.02
High	High	Low	No	0.12	0.6	0.6	0.6
High	High	High	Yes	0.3	0.3	0.3	0.3
High	High	High	No	0.95	0.95	0.95	0.95
Medium	Low	Low	Yes	0.0	0.0	0.01	0.01
Medium	Low	Low	No	0.03	0.1	0.1	0.1
Medium	Low	High	Yes	0.05	0.2	0.2	0.2
Medium	Low	High	No	0.03	0.3	0.3	0.3

Table A-1 (continued)

Medium	High	Low	Yes	0.01	0.05	0.05	0.05
Medium	High	Low	No	0.03	0.1	0.1	0.1
Medium	High	High	Yes	0.03	0.1	0.1	0.1
Medium	High	High	No	0.03	0.3	0.3	0.3
Low	Low	Low	Yes	0.0	0.0	0.001	0.00
Low	Low	Low	No	0.001	0.005	0.05	0.05
Low	Low	High	Yes	0.0	0.0	0.001	0.001
Low	Low	High	No	0.01	0.03	0.1	0.1
Low	High	Low	Yes	0.0	0.0	0.001	0.001
Low	High	Low	No	0.001	0.005	0.05	0.05
Low	High	High	Yes	0.0	0.0	0.005	0.005
Low	High	High	No	0.02	0.05	0.2	0.2

*T = 0.0 corresponds to when the debris hits the drywell floor.

Sources of Uncertainty

Sources of uncertainty included the rather coarse description of the initial conditions (e.g., high and low for the various parameter levels); the temperature at which the drywell shell will fail; the ability for the debris to form a stable crust; and the heat-transfer coefficient between the crust and the debris.

Correlations with Other Variables

No correlations were discussed between other variables in the event trees and the variables discussed as part of this issue.

Suggested Methods for Reducing Uncertainty

The Expert indicated that more precise initial conditions would have allowed him to "get his hands around the problem" more easily but would not have totally reduced the uncertainty associated with this issue. To significantly reduce the uncertainty associated with this issue, the Expert thought that an integrated experiment of this issue should be performed with a scaled model of a Mark I containment. From this experiment, meaningful information about debris-flow characteristics, crust formation, and heat-transfer mechanism could be obtained. The Expert felt that enough analytical work and separated effects experiments had already been done and additional work along these lines would not be as beneficial as an integrated experiment.

Expert B's Elicitation

Issue 1: Peach Bottom Drywell Shell Meltdown

Description of Expert B's Rationale/Methodology

The Expert based his assessment on a two-dimensional heat-conduction model of the drywell shell. The model included convection from the debris; heat transfer from the debris surface by either radiation or boiling heat transfer (for cases with water); radiation and convection from the back side of the shell; and heat transfer to the concrete. The model also allowed the Expert to vary both the debris temperature and the debris-shell heat-transfer coefficient as a function of time. The Expert varied the various parameters in his model to assess their effects on the shell temperature. In addition, he calculated the shell temperature when CORCON results for Peach Bottom were used as input to his model. Based on these calculations, he was able to assess the effects of the various parameters on the drywell shell temperature. The Expert concluded that drywell shell failure was likely except for cases with shallow debris layers cooled by water, and with inefficient heat transfer. With very efficient heat transfer, coolant addition was not effective, and, except for when the shell fails rapidly, back side heat losses were small.

In his assessment, the Expert considered failure of the drywell shell by both melting and creep rupture. He assumed that the failure temperature (by creep rupture) was 1300 K. He stated that the failure temperature was uncertain because if only a small area of the shell was heated the failure temperature might be quite different than if the shell was heated circumferentially.

Several factors that the Expert did not feel were important were the decay power level and the addition of water to the debris after the debris has been deposited on the drywell floor. The Expert believed that the difference between the decay power at 2 h and 10 h would have only a negligible effect and, therefore, was not included as a parameter in his assessment.

The Expert characterized the accident by two major time regimes: before 10 min. and after 10 min. During the first time regime the debris flows across the drywell floor to the shell and piles up against the shell in a localized area. During the second time regime the debris spreads out across the drywell floor. During the first time regime the shell heats up quite rapidly but only in a localized area, whereas during the second time regime more shell area is exposed to the debris but the heatup process is much slower.

The Expert indicated that the amount of superheat associated with the debris was mainly important for early times. Conversely, the amount of unoxidized metal in the debris was mainly important during the late time regime. For cases with a high unoxidized metal content in the debris, the result would be rapid initial ablation of the concrete, high gas release, and a high heat source from the chemical reactions. The water on the

drywell floor affects the debris temperature during both the early and late time regimes. During the early time regime the water in the cavity has the potential to quench the debris. During the late time regime the main effect of water was to transfer heat away from the debris by boiling heat transfer. The effect of water, however, was more important during the early time regime. The Expert gave little credit for water because he felt that it was unlikely the debris would be quenched in the pool of water under the vessel. To quench the debris, significant debris fragmentation (fragments less than 1 cm) must occur and sufficient water must be present. The Expert believed that fine fragmentation was unlikely. Also, the Expert believed much of the "rat's nest" of structure below the vessel would be melted by the flowing debris and a larger opening would be created, making fine fragmentation even less likely. Because the water pool in Peach Bottom has a maximum depth of less than 3 ft, the Expert concluded that debris quenching appeared unlikely. The presence of water could also reduce the flow of molten debris primarily as a result of cooling of the leading edge of the flowing debris. The Expert suspected, however, that water would have a significant impact only for scenarios in which the melt superheat was quite low.

Results of Expert B's Elicitation

The Expert divided the various scenarios into three basic cases: "plop" type failure, low-pressure penetration failure, and high-pressure penetration failure. For each case, various parameters were chosen from the table in the Issue Description and a series of scenarios was assessed. For each scenario, the Expert assessed the probability of drywell shell failure for five different times: 5 min, 10 min, 3 h, 5 h, and when CCI releases are negligible (approximately 7 to 8 h). The cumulative probabilities of drywell shell failure for the various scenarios are presented in Table B-1.

"Plop" Type Failure. No Water

For this case, the Expert combined the high- and low-pressure parameters. In addition, he assumed the amount of superheat associated with the debris must be high. He based his assessment on a debris flow rate of at least 1000 kg/s (120 metric tons of debris deposited in the cavity in 2 min), and he assumed the debris had at least 250 K of superheat. Based on his calculations, failure of the drywell shell appeared likely within minutes of vessel failure, and the amount of metallic material in the debris had essentially no effect.

"Plop" Type Failure. Water

Since high superheat had been assumed for this case and quenching of the melt appeared unlikely, the probabilities of shell failure were not greatly different from the previous case values. The Expert had given some credit for cooling of the melt by the water, which shifted some of the probability to later times, however, failure still appeared likely within 1 h.

Low-Pressure Penetration Failure. Low Superheat. No Water

Although the Expert's calculations indicated that shell failure was assured within 1 h, he gave a significant probability of failure to the 1- to 3-h time interval. This reflects uncertainty in the nature of the flow and crusting behavior for the low superheat cases. There was a slight reduction in the probabilities of failure for the low unoxidized metal case since the failure times were long enough that the chemical reaction energy source may have given out if the metal became fully oxidized. This would occur only for very high in-vessel oxidation.

Low-Pressure Penetration Failure. Low Superheat. Water

The Expert felt this case offered the greatest potential for delaying or perhaps even preventing shell failure since it involved slow flow, low superheat, low unoxidized metal content, and additional cooling of the melt and the shell due to water. The probabilities of early failure were reduced due to the effect of water on the flow of low superheat material (water, however, would not have prevented contact with the drywell shell). Water also made crust formation more likely under low superheat conditions, thereby reducing the rate of heat flow to the shell, and extending the time required for failure. Again, the effect of the unoxidized metal content was only significant for failure times greater than 1 h. In arriving at the failure probabilities, the Expert has tried to filter in his uncertainty regarding coolant effectiveness and debris-to-liner heat transfer.

Low-Pressure Penetration Failure. High Superheat. No Water

The Expert believes the formation of a crust upon contact with the shell was unlikely because of the high debris superheat. As a result, drywell shell failure within minutes of initial debris contact seemed assured. The amount of unoxidized metal in the debris was concluded to have no effect on the shell failure probabilities because of the rapid failure times.

Low-Pressure Penetration Failure. High Superheat. Water

The Expert believed the presence of water would have only a small effect on shell heatup. Because crusting is unlikely for high superheats, the shell failed quite early and the coolant had little effect on the failure probabilities. The amount of unoxidized metal in the debris also had little effect because failure occurred before metal oxidation approached completion.

High-Pressure Penetration Failure. No Water

Based on results from direct containment heating (DCH) experiments conducted at Sandia National Laboratories, the Expert felt that the debris ejected under high pressure would impact the drywell shell as a rapidly flowing jet. Because the heat-transfer rate during the impingement of the jet would be even higher than for the flowing melt, early failure of the shell was even more likely than for the low-pressure cases. The initial amount of debris superheat was not important because the chemical energy

Table B-1
Cumulative Probability of Drywell Shell Failure

Failure Type	Scenario Parameters				Time*					
	Pressure	Δ Metal	Superheat	Water	5 min	10 min	1 h	3 h	5 h	CCI Neg
Large	-	-	-	No	0.6	0.9	1.0	1.0	1.0	1.0
Large	-	-	-	Yes	0.4	0.7	0.98	1.0	1.0	1.0
Small	Low	Low	Low	No	0.2	0.4	0.85	0.95	1.0	1.0
Small	Low	High	Low	No	0.2	0.4	0.85	1.0	1.0	1.0
Small	Low	Low	Low	Yes	0.1	0.3	0.7	0.85	0.93	0.95
Small	Low	High	Low	Yes	0.1	0.3	0.7	0.9	0.98	1.0
Small	Low	-	High	No	0.5	0.85	1.0	1.0	1.0	1.0
Small	Low	-	High	Yes	0.33	0.67	0.9	1.0	1.0	1.0
Small	High	Low	-	No	0.5	0.9	0.95	1.0	1.0	1.0
Small	High	High	-	No	0.6	0.95	1.0	1.0	1.0	1.0
Small	High	Low	-	Yes	0.4	0.85	0.9	0.95	1.0	1.0
Small	High	High	-	Yes	0.5	0.9	0.95	1.0	1.0	1.0

* T = 0.0 corresponds to when the debris hits the drywell floor.

release during metal oxidation controls the temperature of the jet. After the blowdown, the Expert believed the probability distribution would approach those of the low-pressure cases.

High-Pressure Penetration Failure. Water

The Expert referenced experiments at Sandia National Laboratories as basis for his conclusion that water is not a significant benefit in a high-pressure accident, at least for early times. In these experiments in which melt was injected into a water-filled cavity at high pressure, the water was observed to remove heat effectively only from the leading edge of the jet. The rapid pressure rise in the cavity then displaced the water ahead of the jet and the remaining portion of the jet was essentially unaffected by the water.

Sources of Uncertainty

The major sources of uncertainty were the rather coarse description of the initial conditions (i.e., high and low for the various parameter levels), and the effect of water on the drywell shell 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

Suggested Methods for Reducing Uncertainty

The Expert indicated that if initial conditions were defined more precisely (i.e., actual values for the various parameters) the uncertainty associated with the initial conditions could be reduced. However, this would require an enormous increase in the number of cases that would have to be analyzed.

Expert C's Elicitation

Issue 1: Peach Bottom Drywell Meltthrough

Description of Expert C's Rationale/Methodology

Scenarios Considered by Expert

Expert C considered three general scenarios--each with and without water:

1. Vessel failure by penetration failure; low pressure in the vessel at the time the debris is released from the vessel; low debris superheat at the time of debris egress; and a high percentage of unoxidized metal available in the debris after vessel breach.
2. Vessel failure in the plop mode (plop was the phrase that was used at the elicitation meeting to designate a large coherent drop of debris into the cavity; this Expert defined the plop as about 70 metric tons of debris); high pressure at vessel breach; high superheat in the debris upon egress from the vessel; and an intermediate amount of unoxidized metal available in the debris after vessel breach (the Expert defined intermediate as about 50% of the original amount of unoxidized metal).
3. Vessel failure by penetration failure; high pressure at vessel breach (1000 psia) causing a jet expulsion of the debris; low superheat in the debris; and a high percentage of unoxidized metal available in the debris after vessel breach.

The Expert felt that, for the current level of resolution, the phenomenology would be similar for all percentages of unoxidized metal available in the debris after vessel breach greater than 25% (he did not feel that it was credible to predict percentages less than 25%). He also felt that the level of decay heat power in the debris was inconsequential -- that the zirconium oxidation provided enough energy to drive the CCI.

All other variables are taken into account in the curves that bound the initial or central curve.

Predicted Phenomenological Progression of Events and Rationale in Each Scenario

Scenario A

1. The Expert assumed that a penetration failure will result in a molten core flow rate of about 100 kg/s. The range of this value could be from 50 to 200 kg/s.
2. The flow continues unimpeded through the materials directly below the reactor vessel (the CRD and in-core instrumentation material--the "rat's nest"). The rationale for this unimpeded flow is that the flow width would be relatively narrow and would have a direct line of sight through the "rat's nest."

3. The molten core quickly melts through the steel sump pit cover directly beneath the reactor vessel and begins an aggressive CCI in the sump pit. The sump pit fills up by the time the collapsed level of molten debris reaches one half of the sump pit depth. The time elapsed from vessel failure to this point is about 4 min.
4. In the next 6 min, about 5 m³ of debris will fill the cavity, fail the door in the cavity, spread out in an area outside the cavity that will cover a 90-degree section of the drywell floor, and will contact the drywell shell. The depth of the debris will be around 10 cm. (The inclination of the floor—about 1 cm—will not have a large impact on the progression.)
5. If the debris was covered with 15 cm of water it would take about 15 min to boil off. This assumes a heat flux from the debris to the water of about 0.1 W/cm². The effect of the water is to delay the spread, it does not have an order-of-magnitude effect. A crust could form, but would reheat and melt in this scenario.
6. The Expert's best estimate of the time for the debris to reach the steel shell with 15 cm of water on the floor is therefore in the vicinity of 10 min—this includes the competing effects of the cooling by the water and the heating by the CCI. The Expert believes that the flow of the debris is hydrodynamically limited—it is not limited by heat transfer mechanisms.
7. Once the debris contacts the drywell shell, the Expert relied on the ablation analysis in Reference C-1. The Expert felt that even if it took a relatively long time to ablate (50 min), that the tensile strength of the shell would be lost within minutes, resulting in failure of the shell.

Scenario B

1. In this scenario, the Expert considered a coherent drop of about 70 metric tons of debris—this is equivalent to about 10 m³ of debris.
2. He felt that the debris would spread over the pedestal region and half of the drywell floor (about 70 m²), and would be about 15 cm deep.
3. Any water in the drywell at the time of vessel failure would be pushed out of the way. The Expert assumed that there was 10 cm of water, but assumed that it would end up in the region of the drywell that the debris did not occupy. Consequently, he did not give any credit for the water. He also stated that any effect of the water will be quickly lost; there is not enough water to negate the large amount of zirconium available.
4. The Expert stated that the debris could freeze at the debris/concrete interface and that the concrete will still outgas. The water in the concrete will evaporate into the debris and the steam will oxidize the zirconium. The zirconium oxidation will create the energy necessary to drive the endothermic CCI. The steam coming out of the concrete will

equilibrate both thermally and chemically within a few centimeters of the debris/concrete boundary.

5. The Expert does not believe that any crusts will form; data show that, when superheated, metallic melts do not support crusts. It does not matter if crusts form on the periphery of the spread. Any crusts that do form will be melted by the energy from the vigorous zirconium oxidation.
6. Shell contact will occur within minutes. The Expert felt that the heat-transfer coefficient between the debris and the shell would be on the order of $2000 \text{ W/(m}^2 \text{ K)}$, not 1000. He felt that failure would occur rapidly.
7. The Expert felt that the large amount of zirconium available in the BWR debris is the most important parameter in this problem. The effect of the decay heat power is negligible.

Scenario C

1. The Expert considered this a high-pressure melt ejection scenario.
2. The Expert assumed that the debris flow rates would be about a factor of two greater than the flow rates in Scenario A (200 kg/s in this scenario.)
3. The Expert felt that the first part of the melt (about 5%) may lose heat melting a hole through the rat's nest, but that the rest of the melt (95%) will go through the same hole without losing a significant amount of energy.
4. The Expert felt that the debris would probably hit the pedestal floor in a coherent jet.
5. If there was water in the sump, it would probably be displaced by an FCI.
6. Either the molten stream will hit the pedestal and be deflected, or the melt will be atomized by the gases produced. Either way there will be a spray of highly metallic zirconium out the drywell door. There will be an area of high heat transfer directly outside the pedestal doorway.
7. The zirconium will react with steam in flight and will heat up—it will not be cooled. All indications are that this will behave like a plasma jet.
8. In this scenario, it is almost impossible to prevent an instantaneous failure of the drywell shell. The debris transit time would be on the order of seconds, the ablation time about 1 min.

Results of Expert C's Elicitation

The results of this Expert's elicitations are presented in Figures C-1 through C-3. Figure C-1 presents the results of the elicitation of Scenario A, Figure C-2 presents the results of the elicitation of Scenario B, and Figure C-3 presents the results of the elicitation of Scenario C. The curves on Figures C-1 through C-3 are CFPDs—the y axis represents the probability of drywell shell failure and the x axis represents the time to failure.

Three curves are shown in Figure C-1. The center curve is the Expert's best estimate—the rationale is provided in the previous section. The curve to the left is the upper bound CFPD for the scenario and the curve to the right is the lower bound CFPD.

The upper bound CFPD for Scenario A specifically includes the following considerations: (1) little or no water on the drywell and pedestal floor; (2) a high debris flow rate from the vessel (200 to 300 kg/s); (3) a low resistance to debris spreading; and (4) a higher superheat. The lower bound CFPD for Scenario A considers (1) a lot of water available in the drywell; (2) a low debris flow rate from the vessel (< 100 kg); and (3) more material retardation of the debris flow.

Figure C-2 includes two CFPDs representative of Scenario B; the difference between the two is due to the presence of water. The CFPD on the left represents a scenario in which there is little or no water available for debris quenching. If there is water available, the events are shifted in time by a few minutes, resulting in the CFPD on the right.

Figure C-3 includes one CFPD; the Expert feels that the drywell shell will fail with little uncertainty in less than 30 min in Scenario C.

Sources of Uncertainty

Scenario A

The Expert felt that most of the uncertainty in this scenario is in the time that it takes for the debris to spread. A fuel-coolant interaction (FCI) in the sump pit could blow the water out and alter the spreading scenario. Inertial effects in the sump could cause the sump to overflow earlier. Expert C felt that a coolable debris bed would result from any scenario in which the debris took over 2 h to reach the shell.

The Expert felt that the effect of high superheat in the debris would only worsen the situation and did not provide a separate case. This and other uncertainties are considered in the uncertainty ranges given.

Scenario B

Factors that could modify the progression of this scenario are an extremely low unoxidized metal content in the debris; low flow from the vessel; low superheat; and a substantial water barrier coupled with a substantial physical barrier.

Figure C-1. Cumulative Failure Probability of Drywell vs. Time for Scenario A.

Figure C-2. Cumulative Failure Probability of Drywell vs. Time for Scenario B.

Figure C-3. Cumulative Failure Probability of Drywell vs. Time for Scenario C.

Scenario C

There are some phenomena that could limit the effect of the plasma torch. If the hole in the reactor pressure vessel opened up more, it could stop this plasma torch. If there was enough water to interact with the entire debris, the scenario would be impacted; however, the Expert felt that there would be a low probability that there would be that much water.

The Expert felt that the unoxidized zirconium remaining in the debris would have to be lower than any plausible value ($< 15\%$) to impact the scenario. He also felt that the rat's nest would not have more than a 5% effect, and that the amount of superheat would not impact this scenario.

REFERENCE

- C-1. G. A. Greene, K. R. Perkins, and S. A. Hodge, "Mark I Containment Drywell, Impact of Core/Concrete Interactions on Containment Integrity and Failure of the Drywell Liner," in Source Term Evaluation for Accident Conditions, IAEA, Vienna, Austria, IAEA-SM-281, p. 429, 1985.

Expert D's Elicitation

Issue 1: Peach Bottom Drywell Meltthrough

Description of Expert D's Rationale/Methodology

Scenarios Considered by Expert

The following scenarios were considered by the Expert:

A. Scenarios with debris flow > 100 kg/s and low pressure upon debris egress

- A1--Metallic debris,* low superheat,** water available
- A2--Metallic debris, high superheat,*** water available
- A3--Oxidic**** debris, low superheat, water available
- A4--Oxidic debris, high superheat, water available
- A5--Metallic debris, low superheat, no water available
- A6--Metallic debris, high superheat, no water available
- A7--Oxidic debris, low superheat, no water available
- A8--Oxidic debris, high superheat, no water available.

B. Scenarios with debris flow > 50 kg/s and < 100 kg/s, and low pressure upon debris egress

- B1--Metallic debris, low superheat, water available
- B2--Metallic debris, high superheat, water available
- B3--Oxidic debris, low superheat, water available
- B4--Oxidic debris, high superheat, water available
- B5--Metallic debris, low superheat, no water available
- B6--Metallic debris, high superheat, no water available
- B7--Oxidic debris, low superheat, no water available
- B8--Oxidic debris, high superheat, no water available

C. Scenarios with debris flow < 50 kg/s and low pressure upon debris egress

- C1--Metallic debris, low superheat, water available
- C2--Metallic debris, high superheat, water available
- C3--Oxidic debris, low superheat, water available
- C4--Oxidic debris, high superheat, water available
- C5--Metallic debris, low superheat, no water available
- C6--Metallic debris, high superheat, no water available
- C7--Oxidic debris, low superheat, no water available
- C8--Oxidic debris, high superheat, no water available

*Metallic = mix of steel, B4C, Zr

**Low superheat = < 100 K

***High superheat = > 100 K

****Oxidic = UO₂, ZrO₂, Steel, B4C, Zr

D. Scenarios with debris flow > 100 kg/s and high pressure upon debris egress

- D1--Low superheat, water available
- D2--High superheat, water available
- D3--Low superheat, no water available
- D4--High superheat, no water available

Each of the scenarios is represented by an event tree; the 24 low-pressure scenarios are represented by a common logic structure, and the four high-pressure scenarios are represented by a common logic structure. The top events on the event trees represent the parameters that define the scenarios presented in Section I. The probability of drywell shell failure and the best estimate of the time of that failure are given for each branch on the individual event trees.

The entire elicitation was spent evaluating the probabilities for each of the branches.

Results of Expert D's Elicitation

The results of the Expert's elicitation are presented in the following event trees.

CASE: A1

CASE: A2

CASE: A3

CASE: A4

CASE: A5

CASE: A6

CASE: A7

CASE: A8

CASE: B1/B3

EFFECT OF BARRIER	LOSS OF SUPER- HEAT	CRUST STABLE	PROB OF FAILURE	TIME OF FAILURE
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CASE: B2/B4

EFFECT OF BARRIER	LOSS OF SUPER- HEAT	CRUST STABLE	PROB OF FAILURE	TIME OF FAILURE
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CASE: B5/B7

EFFECT OF BARRIER	LOSS OF SUPER- HEAT	CRUST STABLE	PROB OF FAILURE	TIME OF FAILURE
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CASE: B6/B8

EFFECT OF BARRIER	LOSS OF SUPER- HEAT	CRUST STABLE	PROB OF FAILURE	TIME OF FAILURE
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CASE: C1/C3

EFFECT OF BARRIER	LOSS OF SUPER- HEAT	CRUST STABLE	PROB OF FAILURE	TIME OF FAILURE
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CASE: C2/C4

EFFECT OF BARRIER	LOSS OF SUPER- HEAT	CRUST STABLE	PROB OF FAILURE	TIME OF FAILURE
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CASE: C5/C7

EFFECT OF BARRIER	LOSS OF SUPER- HEAT	CRUST STABLE	PROB OF FAILURE	TIME OF FAILURE
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CASE: C6/C8

EFFECT OF BARRIER	LOSS OF SUPER- HEAT	CRUST STABLE	PROB OF FAILURE	TIME OF FAILURE
-------------------------	---------------------------	-----------------	-----------------------	--------------------

CASE: D1/D2

CASE: D3/D4

Expert E's Elicitation

Issue 1: Peach Bottom Drywell Meltdown

Description of Expert E's Rationale/Methodology

The Expert developed an event tree containing the conditions which he felt, after his review of extant analysis and his own parametric calculations, would be the dominant physical conditions that would influence the progression of the drywell liner attack. The major analyses were (1) MELCOR--showed low enthalpy, stratified debris, 13% oxidation, metals then metals + oxides then oxides; and (2) IDCOR MAAP--homogenized, high temperature, no coolability, large pour (1 mt/s), mostly molten, low zirconium. If no water was present, both predicted quick failure. With water present, MELCOR predicted no failure but MAAP predicted failure.

The primary factor affecting the probability of failure was the condition of the melt mass: (a) continuous mass approaching the liner; or (b) dispersed mass approaching the liner. Parameters affecting this condition were (1) vessel pressure; (2) rate of pour from vessel; (3) presence of water in the reactor cavity; and (4) possibility of FCIs. The first three parameters are determined by the accident progression and the results of the in-vessel expert elicitation. The Expert defined two ranges for each parameter and then assessed a probability distribution for drywell liner meltdown for each of the seven resulting cases, taking into account the uncertainties within each range and other underlying parameter uncertainties.

Continuous Melt

For a continuous mass of melt approaching the liner, the basic problem is: For what depth of material and what heat-transfer rate will drywell liner temperatures exceed the liner failure temperature? The Expert performed a sensitivity calculation using a model of the drywell liner and varying both the depth of the melt and the heat-transfer rate. The Expert then assessed the effect of various initial conditions such as pour rate, composition, enthalpy (implies % molten and temperature), and zirconium content (implies energy release due to CCI). The variables are connected by the melt sequence (i.e., a large pour of 1 mt/s will have high temperatures and be homogeneously mixed with very low zirconium oxidation; a small pour of .1 mt/s will have a low temperature and be stratified with a low zirconium oxidation).

Dispersed Melt

The Expert considered two mechanisms for dispersal of the melt direct containment heating (DCH) and FCIs. For DCH, two subconditions were considered: (1) no water, and (2) water, like an FCI. For FCI, water must be present either in-vessel or in-pedestal. A review of FCI analyses was performed and it was determined that FCI was favored for large pours, and either was quenched and dispersed immediately with subsequent heatup to MCCI or only partially quenched with immediate MCCI.

Results of Expert E's Elicitation

First the relative likelihood of the liner failure was assessed to get an overall ranking and then the probability distribution for each of the seven scenarios was assessed.

The seven scenarios are:

1. High pressure (1000 psi), water;
2. High pressure (1000 psi), no water;
3. Low pressure (< 200 psi), high pour (1 mt/s), water, FCI;
4. Low pressure (< 200 psi), high pour (1 mt/s), water, no FCI;
5. Low pressure (< 200 psi), high pour (1 mt/s), no water;
6. Low pressure (< 200 psi), low pour (.1 mt/s), water; and
7. Low pressure (< 200 psi), low pour (.1 mt/s), no water.

The relative likelihood of failure was estimated as such: scenarios 2 and 5 were most likely, then 7, 4, 1, and 3 were equally likely, followed by 6. The total likelihood of liner failure for each scenario was then assessed: $P_f(2) = P_f(5) = 1$, $P_f(7) = 1$, $P_f(4) = .5$, $P_f(1) = .05$, $P_f(3) = .04$, and $P_f(6) = 0$. $P_f(7)$ was greater than $P_f(4)$ at 1 h or more, equal at 10 min, and less at 2 min. The failure for scenarios 1 and 3 was judged to be slightly different.

The probability distributions are:

<u>Scenario</u>	<u>Time</u>					
	<u>0</u>	<u>2 min</u>	<u>10 min</u>	<u>1 h</u>	<u>2 h</u>	<u>10 h</u>
1	0	0.05	0.05	0.05	0.05	0.05
2	0	1.0	1.0	1.0	1.0	1.0
3	0	0.04	0.04	0.04	0.04	0.04
4	0	0.5	0.5	0.5	0.5	0.5
5	0	1.0	1.0	1.0	1.0	1.0
6	0	0.0	0.0	0.0	0.0	0.0
7	0	0.1	0.5	1.0	1.0	1.0

Sources of Uncertainty

The major source of uncertainty was the rather coarse description of the initial conditions and the effect of water on the drywell shell temperature.

Correlations with Other Variables

The correlations with variables to be supplied by the in-vessel group or the accident sequence were considered in the event tree decomposition. All other variables were considered in the uncertainty for each case.

Suggested Methods for Reducing Uncertainties

The Expert indicated that if the initial conditions could be specified more precisely, then some of the uncertainties could be reduced. However, as a result of the in-vessel group results, the largest uncertainties come from difficulties in understanding the core-melt progression in-vessel which would require an exorbitant effort to resolve for this project.

Expert F's Elicitation

Issue 1: Peach Bottom Drywell Meltthrough

Description of Expert F's Rationale/Methodology

Expert F constructed an event tree based on the various conditions and parameters that he judged to have the most significant effects based on his own and extant analysis. He then assessed ranges for these parameters based on the magnitude of the possible effects. The parameters are (1) pour rate--three ranges were selected (< 50 kg/s, 50-100 kg/s, > 100 kg/s); (2) pressure--two ranges were selected (HI, LOW); (3) presence of water in cavity (YES, NO); (4) type of melt--three values were selected: (oxide, mixture, and metallic); (5) melt superheat--two values were selected (HI, LOW); and (6) zirconium values were selected (HI, LOW). In addition, the possibility of FCI was assessed for one case.

Assumptions

1. The pour was assumed to come out fast initially and then slow down.
2. The melt was always coolable when water was present, even with FCI, since good crusts are formed.
3. Low zirconium was 30% of total metallic content of melt.
4. Decay heat was not important.
5. Pours separated by more than 20 min should be treated as separate.
6. The total mass ejected from vessel that begins to threaten the liner (necessary to get 5-cm depth) is 100 tons (45 metric tons).
7. With water present the total mass is not important; without water it's not important if the melt is oxidic.

Results of Expert F's Elicitation

The Expert's results are given on the next page.

<u>Scenario</u>	<u>Pour</u>		<u>Water</u>	<u>Type</u>	<u>Super</u>	<u>Zr</u>	<u>FCI</u>	<u>Prob.</u>
	<u>Rate</u>	<u>Press</u>			<u>Heat</u>			
1	< 50	H,L	Y	-	-	-	-	.001
2	< 50	H,L	N	OX	-	-	-	.001
3	< 50	H,L	N	MIX	L	-	-	.001
4	< 50	H,L	N	MIX	H	-	-	.01
5	< 50	H,L	N	MET	L	L	-	.001
6	< 50	H,L	N	MET	L	H	-	.05
7	< 50	H,L	N	MET	H	L	-	.05
8	< 50	H,L	N	MET	H	H	-	.1
9	50-100	H,L	Y	OX	-	-	-	.001
10	50-100	H,L	Y	MET	-	-	-	.01
11	50-100	H,L	N	OX	-	-	-	.001
12	50-100	H,L	N	MIX	L	-	-	.001
13	50-100	H,L	N	MIX	H	-	-	.1
14	50-100	H,L	N	MET	L	L	-	.1
15	50-100	H,L	N	MET	L	H	-	.2
16	50-100	H,L	N	MET	H	-	-	.5
17	> 100	H,L	Y	OX	L	-	-	.01
18	> 100	H,L	Y	OX	H	-	-	.05
19	> 100	H,L	Y	MIX	L	-	-	.02
20	> 100	H,L	Y	MIX	H	-	-	.1
21	> 100	H,L	Y	MET	L	-	-	.05
22	> 100	H,L	Y	MET	H	-	.95	.05
23	> 100	H,L	Y	MET	H	-	.05	.3
24	> 100	L	N	OX	L	-	-	.1
25	> 100	L	N	OX	H	-	-	.5
26	> 100	L	N	M	L	L	-	.2
27	> 100	L	N	M	L	H	-	.5
28	> 100	L	N	M	H	-	-	.999
29	> 100	H	N	OX	L	-	-	.2
30	> 100	H	N	OX	H	-	-	.999
31	> 100	H	N	M	-	-	-	.999

The Expert judged that the probability of failure for high zirconium pours was twice that of low zirconium pours except for the high pour case where it was 2.5 times.

The time of failure was assessed independently and depended on whether the melt was oxidic or metallic, and whether water was present. The start time was from the point of 5 cm of corium (about 100 tons of corium).

<u>Case</u>	<u>Time</u>		
	<u>2 min</u>	<u>10 min</u>	<u>1 h</u>
Oxidic, no water	0.1	1.0	1
Metallic, no water	1.0	1.0	1
Oxidic, water	0.03	0.3	1
Metallic, water	0.3	1.0	1

Sources of Uncertainty

The major source of uncertainty was the rather coarse description of the initial conditions and the effect of water on the drywell shell temperature.

Correlations with Other Variables

The correlations with variables to be supplied by the in-vessel group or the accident sequence were considered in the event tree decomposition. All other variables were considered in the uncertainty for each case.

Suggested Methods for Reducing Uncertainty

The Expert indicated that if the initial conditions could be specified more precisely, then some of the uncertainties could be reduced. However, as a result of the in-vessel group results, the largest uncertainties come from difficulties in understanding the core-melt progression in-vessel which would require an exorbitant effort to resolve for this project.

6.2 MCCI Issue 2: Grand Gulf Pedestal Erosion

Summary and Aggregation of MCCI Issue 2 Grand Gulf Pedestal Erosion

Experts consulted: Dave Bradley, Sandia National Laboratories; Mike Corradini, University of Wisconsin; George Greene, Brookhaven National Laboratory; Mike Hazzan, Stone & Webster; Mujid Kazimi, Massachusetts Institute of Technology; Raj Sehgal, Electric Power Research Institute.

Issue Description

The experts were asked to characterize the uncertainty in the radial erosion of concrete in the Grand Gulf reactor vessel pedestal due to the interaction of core debris with the concrete. In addition, they were asked to quantify the depth of thermal penetration ahead of the erosion front and the probability that radial erosion occurs above the drywell floor.

The suggested scenarios were characterized by six parameters. These six parameters and the various levels associated with each parameter are presented in the table below

Suggested Scenario Parameters

<u>Scenario Parameters</u>	<u>Levels</u>
1. Failure Mode	a. Plop (> 40% of core released at vessel breach) b. Penetration failure of vessel
2. Reactor Pressure Vessel (RPV) Pressure	a. High (1000 psia), b. Low (200 psia)
3. Debris Superheat	a. High (> 100 K) b. Low (< 100 K)
4. Debris Unoxidized Metal Upon Egress From Vessel	a. High % metal - 65% zirconium equivalent initially in debris on concrete (50 to 80%) b. Low % metal - 35% zirconium equivalent initially in debris on concrete (20 to 50%)
5. Water on Drywell Floor	a. Yes (replenished) b. No (not replenished)

<u>Scenario Parameters</u>	<u>Levels</u>
6. Decay Power Level	a. High (soon after scram--2 h b. Low (well after scram--10 h)

The experts were encouraged to select only those scenario parameters which they felt were important to the issue.

After discussion, the experts decided to consider debris flow rate from the vessel rather than failure mode (the flow rates considered were < 50 kg/s, 50 to 100 kg/s, and > 100 kg/s). They also decided that the decay power level and the RPS pressure did not impact the scenario enough to consider as additional parameters.

Summary of Experts' Rationale/Methodology

This issue is coupled with the Grand Gulf pedestal failure issue, considered by the Structural Response Expert Panel. The structural response experts characterized the pedestal failure probability in terms of the thermal front that precedes the debris/concrete erosion front. All six MCC1 experts agreed that the thermal front would penetrate the concrete a few centimeters ahead of the erosion front. For practical purposes, the erosion front and the thermal front were considered as the same front.

Expert A considered variation in the following parameters while addressing the Grand Gulf pedestal erosion issue: amount of zirconium, amount of superheat, and amount of cavity water. Expert A based his rationale on CORCON calculations that he performed and on a review of pertinent experimental results. He felt that the parameter that was most important to this issue was the amount of unoxidized metal in the debris. He explained that the effects of zirconium oxidation, the amount of superheat, and the presence of water would be important primarily during the early stages of the pedestal erosion (during the first several hours). Expert A felt that the zirconium would be depleted in 2 to 2.5 h.

Expert A indicated that the effect of pour rate on pedestal erosion was important shortly after vessel breach. He felt that erosion during this time regime was governed by zirconium oxidation, which was a slower process than the release of debris from the RPV. He concluded that the effect of different pour rates would not be very important to the longer term erosion results. He thought that the effect of decay heat on pedestal erosion was minor and he did not consider variations of that parameter.

Expert B assessed the cases in which the vessel failed while at low pressure. He felt that the high pressure ejection scenarios would result in direct containment heating (DCH) and should be considered elsewhere. Expert B considered the effect on pedestal erosion of large and small pours from the pressure vessel and the effect of water in the pedestal cavity for

the low pressure cases. The size of the pour defines the properties of the core debris. Expert B described a large pour as a homogenous pour with a high enthalpy, a high temperature and a very low amount of zirconium oxidation. He described a small pour as a stratified pour (i.e., metal comes out first followed by the oxides) with an enthalpy lower than that for the high pour, a temperature just above the liquidus temperature, and a low amount of zirconium oxidation (although higher than that for the high pour). For the large pour cases the only effect cavity water had was that it made fuel coolant interactions (FCIs) possible. The Expert thought the FCI case would eventually degenerate into the case without the FCI with an additional time lag of about 1 h. The effect of water in the small pour cases was to partially quench the debris.

Expert B performed bounding calculations based on a hand calculation scheme presented at the introductory meeting by Marty Plys of FAI. He assumed the sideward and downward erosion rates were equal and that the power fraction into the concrete was 0.5 (e.g., 50% of the energy released from the debris enters the concrete and the other 50% is released from the top of the debris pool). He based his calculations on a limestone/common sand concrete. He felt the rebar in the concrete would have a minor effect on erosion rate and was not modeled in his calculations. For the lower bound the Expert used the IDCOR assumption that the core debris is initially quenched and then is reheated by decay heat.

Expert B indicated that there were two time regimes important with regard to the erosion rate. During the first time regime the zirconium is oxidized and the concrete erodes rapidly. After the zirconium has oxidized, the erosion rate is governed by the decay heat and the oxidation of iron. During this time regime the amount of concrete ablated is essentially proportional to the decay heat. The erosion rate during this second time regime is slow compared to the first time regime erosion rate.

Expert C based his distributions on a review of pertinent experimental and analytical results. He felt that no erosion would occur above the drywell floor since the amount of debris would not reach that height. Radiation would spall off a little concrete above that height, but would quickly hit rebar and spallation would cease.

MCCI was judged to cease at approximately 10 h. The volume of the eroded material was judged to be a function of the amount of unoxidized metals available in the debris. Water was assumed to delay the erosion process, but not to otherwise alter the erosion process.

Expert D based his treatment of the issue on experimental and analytical results which he had performed or reviewed in the past. Expert D judged the volume of the eroded material to be a function of the amount of unoxidized metals available in the debris. The concrete was assessed to erode at a 1:1 rate for the radial and vertical directions. Expert D felt that the presence of zirconium enhanced radial erosion relative to vertical. After the zirconium has burned off, the rate of erosion will decrease to about 1/4th of the original rate. The presence of rebar will dilute the melt and keep it liquid longer. Water will not quench the debris and, therefore, will not affect the results much.

Expert E stated that about 45 MW of energy will be generated by the oxidation of zirconium. About 10 MW will be generated after the zirconium oxidation ceases. After the zirconium oxidation ceases, the debris will behave like a hot solid; it will continue to erode through the concrete in the downward direction, but not in the radial direction.

Expert E felt that the zirconium oxidation would cease at 6 h for a limestone concrete/debris interaction. This would increase to 8 h for limestone/common sand concrete. Oxidation of chromium and iron has a minor impact on the scenario. The Expert felt that there could be major uncertainties in the time to zirconium burnout, but that the total concrete eroded would not be altered significantly by changes in zirconium oxidation timing. He also felt that the volumetric erosion rate is conserved; if the radial erosion was underestimated, the axial erosion would have been overestimated. He felt that most of the effects of superheat, water, and zirconium could be represented by simple shifts in the timing of the CCI.

Expert F thought that the volume of concrete eroded at the point that radioactive aerosol release due to CCI ceases was a function of the amount of unoxidized metal in the debris. The presence of water and the flow rate of the debris from the vessel were judged to impact the penetration by changing the duration of CCI. The amount of zirconium left in the debris was felt to be directly proportional to the final volume of concrete eroded. The initial superheat in the debris and the initial level of decay heat in the debris were considered to be unimportant to the final volume eroded. Expert F felt that the period of interest of the CCI would last for 8 h.

Method of Aggregation

In order to accommodate all of the information received in the six elicitations, we had to consider 24 scenarios (Table 6-1). For each scenario we interpolated or extrapolated the information that each individual expert gave us to fill out a CDF for each of the 24 scenarios; tables of cumulative probabilities for radial erosion depths for different times were then produced. There are tables representing the probability of different radial erosion depths at 1, 3, 6, and 10 h.

Table 6-1
Complete Set of Scenarios for Consideration in Aggregation

A) Low flow rate (<50 kg/s)

- A1) High % Metal, High Superheat, Water
- A2) High % Metal, High Superheat, No Water
- A3) High % Metal, Low Superheat, Water
- A4) High % Metal, Low Superheat, No Water
- A5) Low % Metal, High Superheat, Water
- A6) Low % Metal, High Superheat, No Water
- A7) Low % Metal, Low Superheat, Water
- A8) Low % Metal, Low Superheat, No Water

Table 6-1 (continued)

Medium flow rate (50 kg/s < flow rate < 100 kg/s)

- B1) High % Metal, High Superheat, Water
- B2) High % Metal, High Superheat, No Water
- B3) High % Metal, Low Superheat, Water
- B4) High % Metal, Low Superheat, No Water
- B5) Low % Metal, High Superheat, Water
- B6) Low % Metal, High Superheat, No Water
- B7) Low % Metal, Low Superheat, Water
- B8) Low % Metal, Low Superheat, No Water

High flow rate (>100 kg/s--includes pliop and HPME)

- C1) High % Metal, High Superheat, Water
 - C2) High % Metal, High Superheat, No Water
 - C3) High % Metal, Low Superheat, Water
 - C4) High % Metal, Low Superheat, No Water
 - C5) Low % Metal, High Superheat, Water
 - C6) Low % Metal, High Superheat, No Water
 - C7) Low % Metal, Low Superheat, Water
 - C8) Low % Metal, Low Superheat, No Water
-

The rationale for considering the radial erosion depth and not the axial erosion depth is as follows: the structural experts stated that axial erosion depths were not important for this issue. The radial erosion depths and the temperature of the outer rebar group were considered by the structural experts to be the critical factors in evaluating pedestal failure. The MCCI group stated unanimously that the temperature front would precede the erosion face by only a few centimeters.

The observation times were chosen on the basis of CCI source term releases: at 1 h the aerosol generation from the CCI is most vigorous--a suppression pool bypass at this point would be extremely important to risk; at 3 h a large fraction of most radionuclides (except tellurium) have been already been released to the suppression pool (if no suppression pool bypass has occurred); at 6 h and 10 h, most of the radionuclides have been released to the suppression pool, but tellurium releases may still be occurring.

Many of the distributions that resulted from averaging the experts' results were very similar. To simplify the accident progression event tree (APET), an ANOVA analysis (see description of ANOVA in Section 5.6) was performed to reduce the number of cases. Distributions for the following seven groups were implemented into the event tree:

Group 1 -- Water, high % metal, high superheat (all flow rates)

Group 2 -- Water, high % metal, low superheat and
water, low % metal, high superheat (all flow rates)

Group 3 -- Water, low metal, low superheat (all flow rates)

Group 4 -- No water, low flow and
no water, medium flow, low metal

Group 5 -- No water, medium flow, high metal

Group 6 -- No water, high flow, high metal

Group 7 -- No water, high flow, low metal

Specific Assumptions Made to Aggregate Results

Expert A:

The results given in the elicitation were applied to all pour rates.

Expert B:

1. Case 3 was used to represent all scenarios in which a replenishing water supply was present.
2. Case 1 was used for all of the B and C scenarios defined in Table 6-1 (the medium and high flow rate scenarios) in which a replenishing water supply was not present.
3. Case 2 was used for all of the A scenarios defined in Table 6-1 (the low flow rate scenarios) in which a replenishing water supply was not present.
4. The uncertainty ranges were obtained through inspection of the figure provided in the raw elicitation notes. Before the change in slope in all three curves, the uncertainty range (from the .01 quantile to the .99 quantile) was assumed to be ± 10 cm -- after the change in slope, the uncertainty range was assumed to be ± 5 cm.
5. The magnitude of the radial erosion depths were assumed to be equal to the magnitude of the axial erosion depths.

Expert C:

1. Used the median and the bounds given by the Expert to represent the median and the .01 and .99 quantiles for all scenarios.
2. Interpolated for values at 3 h.

Expert D:

1. The values provided by the expert for the large pour and small pour cases were used to represent the A and B scenarios defined in Attachment 1 (the low flow rate and the medium flow rate scenarios.) The values provided by the Expert for the plop cases were used to represent the C scenarios defined in Attachment 1 (the high flow rate cases.)

2. An uncertainty interval (.01 and .99 quantiles) of ± 5 cm for radial erosion values of less than 100 cm and an interval of ± 10 cm for radial erosion values of greater than or equal to 100 cm was assumed.

Expert E:

All assumptions are explained in the elicitation writeup.

Expert F:

All assumptions are explained in the elicitation writeup.

Aggregated Results

Table 6-2
Average of 24 Cases
Cumulative Probability of Different Radial Erosion
Depths at Different Times
(Radial Erosion Depths are in cm)

Scenario	1 Hour					3 Hours				
	1%	25%	50%	75%	99%	1%	25%	50%	75%	99%
A1	0.0	6.0	16.6	23.5	46.7	0.0	16.5	31.4	54.6	69.5
A2	3.5	12.2	21.3	28.4	56.3	11.9	33.2	53.9	63.2	79.5
A3	0.0	4.1	13.4	21.7	48.6	0.0	11.2	30.2	54.5	69.5
A4	2.4	10.5	20.2	28.3	55.2	8.2	29.7	52.0	61.8	76.3
A5	0.0	5.3	11.4	19.5	34.5	0.0	13.9	24.2	45.9	67.7
A6	3.5	11.1	18.4	23.9	39.1	11.9	26.5	41.3	59.6	69.2
A7	0.0	3.6	8.7	19.5	34.5	0.0	10.0	20.9	45.9	67.7
A8	2.4	8.0	17.0	22.4	39.1	8.2	23.1	37.6	59.6	69.2
B1	0.0	6.0	16.7	23.7	50.2	0.0	16.5	31.8	55.3	71.5
B2	3.5	14.6	22.5	30.5	59.2	11.9	33.6	57.2	67.1	84.4
B3	0.0	4.1	13.4	21.9	50.2	0.0	11.2	39.5	55.2	71.5
B4	2.4	11.0	21.3	28.1	57.5	8.2	30.2	54.1	65.7	84.4
B5	0.0	5.3	11.4	19.6	35.5	0.0	13.9	24.5	46.7	67.7
B6	3.5	11.5	19.5	24.9	40.7	11.9	26.9	41.8	63.8	84.0
B7	0.0	3.6	8.7	19.6	35.5	0.0	10.0	21.1	46.7	67.7
B8	2.4	8.0	17.9	23.7	40.7	8.2	23.4	37.9	63.8	84.0
C1	0.0	6.0	17.6	28.8	50.2	0.0	16.5	31.8	55.7	109.0
C2	3.5	14.6	26.9	34.3	59.2	11.9	33.6	57.3	78.0	109.0
C3	0.0	4.1	13.4	28.5	50.2	0.0	11.2	30.5	55.5	109.0
C4	2.4	11.0	24.8	32.2	57.5	8.2	30.2	54.1	77.2	109.0
C5	0.0	5.3	11.4	25.4	37.5	0.0	13.9	24.5	46.7	109.0
C6	3.5	11.5	21.3	29.6	40.7	11.9	26.9	41.8	75.0	109.0
C7	0.0	3.6	8.7	25.4	37.5	0.0	10.0	21.1	46.7	109.0
C8	2.4	8.0	18.8	29.4	40.7	8.2	23.4	37.9	75.0	109.0

Table 6-2 (continued)

Scenario	5 Hours					10 Hours				
	1%	25%	50%	75%	99%	1%	25%	50%	75%	99%
A1	16 0	35 1	53 7	81 6	134 0	38 1	65 8	98 7	114 5	159 0
A2	32 7	55 1	83 4	106 4	134 0	40 0	73 0	109 2	128 8	159 0
A3	16 0	34 3	52 4	81 4	134 0	38 1	64 8	97 5	112 8	159 0
A4	30 8	54 4	82 0	106 4	134 0	40 0	72 1	108 2	127 3	159 0
A5	16 0	28 8	43 2	75 0	134 0	26 9	50 5	81 6	108 3	159 0
A6	24 4	43 9	66 6	106 4	134 0	30 4	58 8	88 8	122 6	159 0
A7	16 0	28 3	42 2	75 0	134 0	26 9	49 8	80 7	108 3	159 0
A8	24 0	43 5	65 9	106 4	134 0	30 3	59 2	88 8	122 8	159 0
B1	16 0	35 4	54 1	82 9	134 0	39 8	66 3	99 8	114 5	159 0
B2	32 8	55 5	84 2	109 9	134 0	40 0	73 0	109 2	128 8	159 0
B3	16 0	34 5	52 7	82 8	134 0	39 4	65 3	98 7	112 8	159 0
B4	30 6	54 7	82 8	109 8	134 0	40 0	72 1	108 2	129 5	159 0
B5	16 0	29 1	43 5	75 0	134 0	28 0	51 0	81 6	108 3	159 0
B6	24 9	44 2	67 2	109 9	134 0	31 5	58 5	89 8	126 5	159 0
B7	16 0	28 5	42 5	75 0	134 0	28 0	50 5	80 7	108 3	159 0
B8	24 3	43 9	66 5	109 9	134 0	31 4	59 0	88 8	126 5	159 0
C1	16 0	35 4	54 1	82 8	134 0	39 6	66 3	98 8	114 5	159 0
C2	32 8	55 5	84 2	109 9	134 0	40 0	73 0	109 2	129 8	159 0
C3	16 0	34 5	52 7	82 8	134 0	39 4	65 3	98 7	112 8	159 0
C4	30 6	54 7	82 8	109 9	134 0	40 0	72 1	108 2	129 5	159 0
C5	16 0	29 1	43 5	75 0	134 0	28 0	51 0	81 6	108 8	159 0
C6	24 9	44 2	67 2	109 9	134 0	31 5	58 5	89 8	126 5	159 0
C7	16 0	28 5	42 5	75 0	134 0	28 0	50 5	80 7	108 3	159 0
C8	24 3	43 9	66 5	109 9	134 0	31 4	59 0	88 8	126 5	159 0

Table 6-3
Average of 7 Cases
Cumulative Probability of Different Radial Erosion
Depths at Different Times
(Radial Erosion Depths are in cm)

Group	1 Hour					3 Hours				
	1%	25%	50%	75%	99%	1%	25%	50%	75%	99%
1	0 0	6 0	16 9	26 5	49 8	0 0	16 5	31 7	55 1	104 8
2	0 0	4 9	12 4	23 1	48 6	0 0	12 7	27 5	51 0	104 4
3	0 0	3 6	8 7	21 5	36 7	0 0	10 0	21 1	46 4	104 4
4	2 6	10 3	18 7	25 7	54 3	8 8	26 6	44 2	61 8	82 5
5	2 7	12 7	21 9	30 0	58 5	8 9	31 9	55 1	88 6	84 4
6	2 7	13 0	25 6	33 8	58 6	8 8	31 9	55 7	77 7	109 0
7	2 6	10 0	20 1	29 5	40 7	8 7	25 1	40 7	75 0	109 0
Group	6 Hours					10 Hours				
	1%	25%	50%	75%	99%	1%	25%	50%	75%	99%
1	16 0	35 3	54 0	82 5	134 0	38 0	66 2	99 2	114 5	159 0
2	0 0	31 3	49 2	79 9	134 0	28 6	58 4	89 1	111 8	159 0
3	16 0	28 4	42 4	75 0	134 0	27 5	50 3	80 7	108 3	159 0
4	24 8	47 4	73 4	107 3	134 0	31 5	63 1	95 8	126 3	159 0
5	31 3	55 1	83 5	109 9	134 0	40 0	72 6	108 8	129 7	159 0
6	31 3	55 1	83 5	109 9	134 0	40 0	72 8	108 6	128 7	159 0
7	24 6	44 1	67 8	109 8	134 0	31 5	59 3	89 2	125 5	159 0

Figure 6.1. Aggregation of MCCI Issue 2. Cumulative Probability of Different Radial Erosion Depths at Different Times.

Individual Elicitations for MCCI Issue 2

Expert A's Elicitation

Issue 2: Pedestal Erosion at Grand Gulf

Description of Expert A's Rationale/Methodology

The scenario parameters that the Expert considered were amount of zirconium, amount of superheat, and cavity water. The Expert based his numbers on the CORCON calculations that he performed and on the review of pertinent experimental results. The Expert felt that the most important parameter was the amount of unoxidized metal in the debris. A high level of unoxidized metal corresponds to approximately 80% unoxidized zirconium, and a low level corresponds to 20% unoxidized zirconium. He indicated that the effects of zirconium oxidation, the amount of superheat, and the presence of water would be primarily important during the early stages of the pedestal erosion (first several hours). The Expert estimated that the zirconium would be depleted in 2 to 2.5 h. The low zirconium cases will have early and late erosion depths which are 50 and 20% of the high zirconium cases, respectively. The Expert thought that the presence of water would have a 50% effect in the early stages and would have an overall effect of 10 to 20%.

The Expert indicated that the effect of pour rate on pedestal erosion is only important shortly after vessel breach. However, he felt erosion during this time regime was governed by zirconium oxidation which occurs more slowly than the pour rate. Thus, the Expert concluded that effects of pour rate would not be very important. In addition, he thought that the effect of decay heat on pedestal erosion was minor and, thus, did not consider it as a parameter.

The Expert stated that the location of maximum radial erosion would occur 1 to 1.5 m above the pedestal floor. The drywell floor is approximately 1.9 m above the pedestal floor. Thus, the Expert concluded that significant radial erosion would not occur above the drywell floor.

It was also the opinion of the Expert that the thermal front would only penetrate into the concrete a few centimeters ahead of the erosion front. The thickness of the pedestal wall is approximately 1.75 m and, therefore, in the context of this issue, the thermal front can be characterized by the erosion front.

Results of Expert A's Elicitation

The Expert provided cumulative probabilities for various pedestal erosion depths at 1, 3, 6, and 10 h for the high unoxidized metal case with high and low superheat. These two distributions will be referred to as the base distributions. The erosion depth accounts for both ablation and thermal penetration (the thermal penetration is only a couple of centimeters ahead of the ablation front). To get the remaining distributions (low zirconium cases and water cases) the base distributions are reduced to account for the effects the parameters have on the erosion depth. A low level of zirconium reduces the base distribution erosion depths by 50, 40, 25, and

20% at 1, 3, 6, and 10 h, respectively. Similarly, the presence of water reduces the base distribution erosion depths by 50, 40, 25, and 20% at 1, 3, 6, and 10 h, respectively. There are eight cases associated with the three scenario parameters. These cases are described in Table A-1. The base distributions (Cases 1 and 3) are presented in Table A-2. The distributions for the eight cases are presented in Table A-3.

Table A-1
Case Descriptions

<u>Case</u>	<u>Unoxidized Metal</u>	<u>Superheat</u>	<u>Water</u>
1	High	High	No
2	High	High	Yes
3	High	Low	No
4	High	Low	Yes
5	Low	High	No
6	Low	High	Yes
7	Low	Low	No
8	Low	Low	Yes

Table A-2
Base Distributions--Erosion Depth Probabilities
for High Level of Unoxidized Metal

<u>Cumulative Probability</u>	<u>Erosion Depth (m)</u>	
	<u>Low Superheat</u>	<u>High Superheat</u>
	<u>1 h*</u>	
0.01	0.05	0.15
0.25	0.15	0.30
0.50	0.25	0.40
0.75	0.35	0.50
0.99	0.40	0.60
	<u>3 h*</u>	
0.01	0.20	0.30
0.20	0.35	0.40
0.50	0.50	0.55
0.75	0.55	0.65
0.99	0.65	0.80

Table A-2 (continued)

<u>Cumulative Probability</u>	<u>Erosion Depth (m)</u>	
	<u>Low Superheat</u>	<u>High Superheat</u>
	<u>6 h*</u>	
0.01	0.45	0.45
0.20	0.55	0.55
0.50	0.65	0.65
0.75	0.85	0.85
0.99	1.00	1.00
	<u>10 h*</u>	
0.01	0.50	0.50
0.20	0.75	0.75
0.50	0.90	0.90
0.90	1.25	1.25
0.99	1.50	1.50

*Time is from start of CCI

Table A-3
Pedestal Radial Erosion Depths (m)

<u>Case</u>	<u>Cumulative Probabilities</u>				
	<u>0.01</u>	<u>0.25</u>	<u>0.50</u>	<u>0.75</u>	<u>0.99</u>
	<u>1 h*</u>				
1	0.150	0.300	0.4000	0.500	0.600
2	0.075	0.150	0.200	0.250	0.300
3	0.050	0.150	0.250	0.350	0.400
4	0.025	0.075	0.125	0.175	0.200
5	0.075	0.150	0.200	0.250	0.300
6	0.038	0.075	0.100	0.125	0.150
7	0.025	0.075	0.125	0.175	0.200
8	0.013	0.038	0.063	0.088	0.100

Table A-3 (continued)

Case	Cumulative Probabilities				
	0.01	0.25	0.50	0.75	0.99
<u>3 h*</u>					
1	0.300	0.400	0.550	0.650	0.800
2	0.180	0.240	0.330	0.390	0.480
3	0.200	0.350	0.500	0.550	0.650
4	0.120	0.210	0.300	0.330	0.390
5	0.180	0.240	0.330	0.390	0.480
6	0.108	0.144	0.198	0.234	0.288
7	0.120	0.210	0.300	0.330	0.390
8	0.072	0.126	0.180	0.198	0.234
<u>6 h*</u>					
1	0.450	0.550	0.650	0.850	1.000
2	0.338	0.413	0.488	0.638	0.750
3	0.450	0.550	0.650	0.850	1.000
4	0.338	0.413	0.488	0.638	0.750
5	0.338	0.413	0.488	0.638	0.750
6	0.253	0.309	0.366	0.478	0.563
7	0.338	0.413	0.488	0.638	0.750
8	0.253	0.309	0.366	0.478	0.563
<u>10 h*</u>					
1	0.500	0.750	0.900	1.250	1.500
2	0.400	0.600	0.720	1.000	1.200
3	0.500	0.750	0.900	1.250	1.500
4	0.400	0.600	0.720	1.000	1.200
5	0.400	0.600	0.720	1.000	1.200
6	0.320	0.480	0.576	0.800	0.960
7	0.400	0.600	0.720	1.000	1.200
8	0.320	0.480	0.576	0.800	0.960

*Times are from start of CCI

Sources of Uncertainty

The Expert indicated that some of the uncertainty stems from the coarse description of the initial conditions. However, the Expert stated that there is still a significant amount of uncertainty associated with this issue that does not stem from the description of the initial conditions. He has reviewed results from a variety of analytical models as well as from various experimental programs, and there is not a general agreement among them.

Expert B's Elicitation

Issue 2: Pedestal Erosion at Grand Gulf

Description of Expert B's Rationale/Methodology

The scenario parameters that the Expert considered were pressure, debris pour rate, and cavity water. The Expert thought that core debris ejected at high pressure would be dispersed and the scenario would follow a DCH path. The effects of DCH were not to be addressed by this panel. Therefore, the Expert only assessed the low-pressure cases. For the low-pressure cases, the Expert considered the effects on pedestal erosion of large and small pours and the effect of water in the pedestal cavity. The size of the pour defines the properties of the core debris. The Expert described a large pour as being a homogenous pour with a high enthalpy, a high temperature and a very low amount of zirconium oxidation. On the other hand, a small pour was described as being a stratified pour (i.e., metal comes out first followed by the oxides) with an enthalpy lower than that for the high pour, a temperature just above the liquidus temperature, and a low amount of zirconium oxidation (although higher than that for the high pour). For the large pour cases the only effect cavity water had was that it made FCIs possible. Although the panel was not asked to assess the effects of FCIs, the Expert thought the FCI case would degenerate into the case without the FCI. However, there would be a time lag associated with the FCI case. The Expert estimated this time lag would be approximately 1 h. For the small pour cases the water's effect was that it partially quenched the debris. The Expert stated that the effects of an FCI for this case would be negligible. The case structure is shown in Figure B-1.

Figure B-1. Case Structure for Grand Gulf Pedestal Erosion

To estimate the concrete erosion depth as a function of time, the Expert performed some bounding calculations. The Expert based his calculations on a hand calculation scheme presented by Marty Plys of FAI.³⁻¹ As an upper bound (fast erosion), the Expert assumed the full core was instantaneously deposited in the cavity at high temperature. He assumed 15% of the zirconium had been oxidized, and used a decay heat level of 1% (short-term station blackout). In addition, he assumed the sideward and downward erosion rates were equal and that the power fraction into the concrete was 0.5 (e.g., 50% of the energy released from the debris enters the concrete and the other 50% is released from the top of the debris pool). He based his calculations on a limestone/common sand concrete. He felt that the rebar in the concrete would have a minor effect on erosion rate and was not modeled in his calculations. Although these are relatively simple hand calculations which do not take into account coking, the Expert felt that these results would be similar to results one would expect from CORCON. Furthermore, because of assumptions he made, the Expert felt his calculations would have faster erosion rates than erosion rates predicted by CORCON. For the lower bound the Expert used the IDCOR assumption that the core debris is initially quenched and then is reheated by decay heat. The shape of this curve is the same as the shape for the upper bound except that it is shifted in time. The Expert estimated that this time shift would be approximately 5 h (i.e., the CCI would begin 5 h after the core was deposited in the cavity).

The Expert indicated that there were two time regimes that were important with regard to the erosion rate. During the first time regime the zirconium is oxidized and the erosion rate is fairly fast. After the zirconium is oxidized, the erosion rate is governed by the decay heat and the oxidation of iron. During this time regime the amount of concrete ablated is essentially proportional to the decay heat. The erosion rate during this second time regime is slow compared to the first time regime erosion rate. The Expert estimated that it would take 4 h to deplete the zirconium.

Results of Expert B's Elicitation

The Expert expressed the pedestal concrete erosion depth in terms of Z_{max} and A_{max} . The term Z_{max} corresponds to the maximum downward erosion depth, measured from the pedestal cavity floor. Similarly, the term A_{max} corresponds to the maximum radial erosion depth, measured from the cavity wall. At each time increment the eroded geometry of the cavity will be a right cylinder. This is illustrated in Figure B-2. The erosion depths, as a function of time, for the upper bound and the lower bound are presented in Table B-1. The Expert expressed the uncertainty in the erosion depth as a time shift. For both curves, the uncertainties at the 1- and 2-m erosion depths are 30 min and 60 min, respectively.

Figure B-2. Eroded Pedestal Geometry

Table B-1
Bounding Calculations for Grand Gulf
Pedestal Erosion Depths

Erosion Depth (m)	Time (h,s)	
	Upper Bound	Lower Bound
Zmax, Armax		
0.0	0.0	5.0
1.0	4.0	9.0
2.0	28.0	33.

The Expert defined three cases: Case 1 corresponds to a large pour with no FCI; Case 2 corresponds to a small pour with no water in the cavity; and Case 3 corresponds to a small pour with water in the cavity. The Expert felt the large pour case corresponded to the upper bound analysis. Because core debris is added to the pedestal cavity at a slower rate for the small pour case than for the large pour case, the Expert thought the erosion for the small pour would still start at time zero but progress at a slower rate. However, the same amount of material is deposited in the cavity for both the large pour and the small pour, and, therefore, the erosion rate for the small pour will eventually catch up to the large pour. The Expert estimated that it would take 1 h longer for the small pour to erode 1 m of concrete than it would for the large pour. After that point, however, the erosion rate would be the same. The difference between Case 2 and Case 3 stems from the water in the cavity. The Expert thought the water in the cavity would initially cool the debris which would result in an initially slower erosion rate. He estimated it would take 1 h longer for 1 m of concrete to be eroded in Case 3 than it would in Case 2. After that point, however, the erosion rate would be the same. These results are summarized in Table B-2.

Table B-2
Grand Gulf Pedestal Erosion Depths for Cases 1, 2, and 3

Erosion Depth (m) <u>Z_{max}, A_{rmax}</u>	<u>Time (h.s)</u>		
	<u>Case 1</u>	<u>Case 2</u>	<u>Case 3</u>
0.0	0.0	0.0	0.0
1.0	4.0	5.0	6.0
2.0	28.0	29.0	30.0

The Expert was certain that significant radial erosion would only occur below the drywell floor elevation.

It was also the opinion of the Expert that the thermal front would only penetrate into the concrete a few centimeters ahead of the erosion front. The Expert stated that the temperature profile through the concrete pedestal wall can be approximated by an exponential decay function.

Sources of Uncertainty

The major source of uncertainty was the rather coarse description of the initial conditions. However, the Expert felt most cases would fall somewhere between his upper and lower bound cases.

REFERENCE

- B-1. M. G. Plys, "Hand Calculations for Core-Concrete Attack and Pedestal Failure Timing with Applications to LaSalle and Grand Gulf," NUREG-1150 Molten Core Containment Interaction Expert Review Group Meeting, Albuquerque, NM, December, 1987 (reproduced in NUREG/CR-4551, Part 6).

Expert C's Elicitation

Issue 2: Pedestal Erosion at Grand Gulf

Description of Expert C's Rationale/Methodology

The Expert considered all of the scenario parameters described in the issue description and based his numbers on a review of pertinent experimental and analytical results. This allowed him to get times for distances penetrated vs. time for various codes and models. He then reevaluated these results based on considerations of the uncertain parameters and models.

Results of Expert C's Elicitation

The Expert thought that the thermal penetration front would be only a few centimeters ahead of the erosion front. Since the thickness of the pedestal wall is approximately 1.75 m, the thermal front can be characterized by the erosion front for this issue.

The Expert thought that no erosion was possible above the drywell floor since the amount of debris would not reach that height. The drywell floor is approximately 1.9 m above the pedestal floor and the Expert assessed that even if some melt was at that elevation the location of maximal erosion would be below the pedestal floor. Radiation would spall off a little concrete but immediately it would hit rebar and little more would occur.

The Expert gave a distribution for radial (dr) and vertical (z) erosion at a specified "critical point," defined to be the point of maximal radial erosion, except in certain cases where another point with only slightly less maximal erosion could be identified with substantially less vertical erosion than that at the maximum point. MCCi was judged to cease for all practical purposes at approximately 10 h. The volume of the eroded material was judged to be strictly a function of the amount of unoxidized metals available from the core. Water was assumed to only delay the erosion process, but not alter the total erosion volume or erosion directions.

Uncertainty about the radial and vertical erosion distances was judged to be a direct function of the erosion direction, expressed as a ratio of dr/z , which was estimated to be between 2:1 and 1:2. For times of 1, 6, and 10 h, a median dr was estimated, as well as a lower and upper bound. Vertical erosion depths were also estimated.

Parameter (cm)	Time (h)		
	1	6	10
dr_{05}	2.5	43	60
dr_{50}	15	75	90
dr_{95}	30	125	140
z_{05}	22	87	112
z_{50}	18	75	105
z_{95}	12	50	87

The condition of melt was assessed as metal rich with 75% of the core, 30% of the zirconium, and no water. The melt was said to proceed almost vertically after 10 h with no further radial erosion.

Sources of Uncertainty

The main uncertainty is in the models. The uncertainty in the physical parameters or initial conditions does not affect the long term erosion distance significantly.

Expert D's Elicitation

Issue 2: Pedestal Erosion at Grand Gulf

Description of Expert D's Rationale/Methodology

The Expert considered all of the scenario parameters described in the issue description and based his numbers on a review of pertinent experimental and analytical results which he had performed or reviewed in the past. The Expert gave tentative results based on Limestone concrete and did three simple calculations for radial, vertical, and both vertical and radial erosion. The concrete at Grand Gulf may be limestone/common sand and the Expert did not consider the effect of the large amount of rebar that is present; he was planning to review these considerations and see if they affected his results. No changes were received so the original elicitation was used.

Results of Expert D's Elicitation

The Expert thought that the thermal penetration front would be only a few centimeters (5 cm) ahead of the erosion front. Since the thickness of the pedestal wall is approximately 1.75 m, the thermal front can be characterized by the erosion front for this issue.

The Expert thought that no erosion was possible above the drywell floor since the amount of debris would not reach that height. The drywell floor is approximately 1.9 m above the pedestal floor and the Expert assessed that even if some melt was at that elevation the location of maximal erosion would be below the pedestal floor. Radiative erosion is not possible if water is present; otherwise, a few centimeters of spallation may be possible, but not a significant amount.

The Expert gave values for radial (dr) and vertical (z) erosion at a specified "critical point," defined to be the point of maximal radial erosion. MCCI was judged to cease for all practical purposes at approximately 10 h. The volume of the eroded material was judged to be strictly a function of the amount of unoxidized metals available from the core. The limestone was assessed to erode at a 1:1 rate for the radial and vertical directions. The presence of zirconium was assessed to enhance radial erosion relative to vertical. With no zirconium present (i.e., after it has burned off), the rate of erosion will decrease to about 1/4th of the original rate. The presence of rebar will dilute the melt and keep it liquid longer. Water will not quench the debris and, therefore, will not affect the results much.

Three scenarios were defined: (1) large pour, (2) small pour, and (3) plop. The plop was assessed at .5 h, then assumed linear until 3 h, after which zirconium depletes and the rate drops to 1/4th of that in the first 3 h, and finally the rate drops to 3/4th of the 3- to 6-h rate to give the 10-h result. For the pours, the 6- and 10-h results will be the same as the plop cases; however, the earlier rate will be slower and constant up to the

6-h point. The rate of erosion is different initially due to the initial conditions, but, after several hours, the effects of the initial conditions are washed out and the final erosion distances and rates all approach the same values.

	<u>Time (h)</u>				
Variable (cm)	.5	1	3	6	10
Pour r_{max}	10	21	63	125	150
Pour $z(r_{max})$	7	16	47	94	113
Plop r_{max}	16	33	100	125	150
Plop $z(r_{max})$	13	25	75	94	113

Sources of Uncertainty

The major contributors to the uncertainty are (1) the lack of definite identification of concrete type; (2) the uncertainty on the amount of rebar; and (3) the effects of the amount of zirconium present.

Expert E's Elicitation

Issue 2: Pedestal Erosion at Grand Gulf

Description of Expert E's Rationale/Methodology

The Expert stated that about 45 MW of energy will be generated by the oxidation of zirconium. About 10 MW will be generated after the zirconium oxidation ceases. After the zirconium oxidation ceases, the debris will behave like a hot solid; it will continue to erode through the concrete in the downward direction, but not in the radial direction.

The Expert stated that for a limestone concrete/debris interaction, the zirconium oxidation would stop at 6 h. If the concrete was limestone/common sand, the zirconium oxidation would go on for 8 h. The oxidation of chromium and iron have a minor impact on the scenario. The Expert felt that there could be major uncertainties in the time to zirconium burnout, but that the total concrete eroded would not be altered significantly by changes in zirconium oxidation timing. He also felt that the volumetric erosion rate is conserved; if the radial erosion was underestimated, the axial erosion would have been overestimated.

Results of Expert's E's Elicitation

The Expert verified that the thermal penetration front preceded the erosion front by no more than a few centimeters.

The Expert defined a base case in which the debris contained low superheat, high zirconium content, and no water. The radial erosion depths for 1, 3, 6, and 10 h for this case are given below:

1 h: 13.33 cm
3 h: 40 cm
6 h: 70 cm
10 h: 90 cm.

The uncertainty on the base case value at six hours were extrapolated for the .01 and .99 quantiles and are presented below:

.01 quantile: 40 cm
.50 quantile: 70 cm
.99 quantile: 130 cm.

The Expert felt that most of the effects of superheat, water, and zirconium could be represented by simple shifts in the timing of the CCI. The Expert felt that the effect of high superheat would be to speed the erosion up by 1/2 h. He felt that the effect of water would be to slow the erosion down by a factor of 0.85 (multiply the time values by a factor of 1.0/.85). The effect of lower zirconium content would be to cause the CCI to burn out in half the time--the erosion depths would be the same as the high zirconium case up until that point.

The values given in the elicitation were for limestone concrete. To account for the fact that Grand Gulf has limestone/common sand concrete, the Expert suggested that we add 2 h to the duration of CCI. (In the limestone base case, the CCI duration is 6 h.)

The median of the base case was modified to represent the effects described above (the process and the medians resulting from the process are presented below). To calculate the .01 and .99 quantiles, the median was multiplied by a the same factor used for the base case, 6-h example--the median was multiplied by 40/70 to get the .01 quantile; the median was multiplied by 130/70 to get the .99 quantile.

Modification of Base Case Medians to Obtain Medians for Other Cases (Radial Erosion Depth [cm])

1. Base case:

1 h	3 h	6 h	10 h
13.33 cm	40 cm	70 cm	90 cm

2. Base case with limestone/common sand (ls/cs)--shift timing by 2 h

3 h	5 h	8 h	12 h
13.33 cm	40 cm	70 cm	90 cm

Interpolate and extrapolate for necessary times:

1 h	3 h	6 h	10 h
4 cm	13.33 cm	50 cm	80 cm

3. No water, high zirconium high superheat, ls/cs--shift case 2 by 1/2 h

.5 h	2.5 h	5.5 h	9.5 h
4 cm	13.33 cm	50 cm	80 cm

Interpolate and extrapolate for necessary times:

1 h	3 h	6 h	10 h
6.33 cm	19.44 cm	53.75 cm	83.75 cm

4. No water, low zirconium low superheat, ls/cs--CCI burns out at 4 h rather than 8; curve stays the same as case 2 until that point

1 h	3 h	6 h	10 h
4 cm	13.33	40 cm	55 cm

5. No water, low zirconium high superheat, ls/cs--shift case 4 by 1/2 h

.5 h	2.5 h	5.5 h	9.5 h
4 cm	13.33	40 cm	55 cm

Interpolate and extrapolate for necessary times:

1 h	3 h	6 h	10 h
6.33 cm	19.44 cm	41.88 cm	56.88 cm

6. Water, high zirconium low super heat, ls/cs--stretch timing on case 2 out by a factor of .85

1.17 h	3.53 h	7.05 h	11.76 h
4 cm	13.33 cm	50 cm	80 cm

Interpolate and extrapolate for necessary times:

1 h	3 h	6 h	10 h
3.3 cm	11.23 cm	38.99 cm	68.75 cm

7. Water, high zirconium high superheat, ls/cs--stretch timing on case 3 out by a factor of .85

1.17 h	3.53 h	7.05 h	11.76 h
6.33 cm	19.44 cm	53.75 cm	83.75 cm

Interpolate and extrapolate for necessary times:

1 h	3 h	6 h	10 h
5.35 cm	16.49 cm	43.46 cm	72.5 cm

8. Water, low zirconium low superheat, ls/cs--stretch timing on case 4 out by a factor of .85

1.17 h	3.53 h	7.05 h	11.76 h
4 cm	13.33	40 cm	55 cm

Interpolate and extrapolate for necessary times:

1 h	3 h	6 h	10 h
3.3 cm	11.23 cm	31.99 cm	49.37 cm

9. Water, low zirconium high superheat, ls/cs--stretch timing on case 5 out by a factor of .85

1.17 h	3.53 h	7.05 h	11.76 h
6.33 cm	19.44 cm	41.88 cm	56.88 cm

Interpolate and extrapolate for necessary times:

1 h	3 h	6 h	10 h
5.35 cm	16.49 cm	35.14 cm	51.25 cm

The values for above cases 2 through 9 were used for both low pour and high pour scenarios in the aggregated results of this issue.

Sources of Uncertainty

This Expert felt that a large part of the uncertainty in this scenario was in the timing of zirconium oxidation.

Expert F's Elicitation

Issue 2: Pedestal Erosion at Grand Gulf

Description of Expert F's Rationale/Methodology

The volume of concrete eroded at the point that radioactive aerosol release due to CCI ceases was thought by this Expert to be essentially a function of the amount of unoxidized metal in the debris. The presence of water and the flow rate of the debris from the vessel were judged to impact the penetration by changing the duration of CCI. The amount of zirconium left in the debris was felt to be directly proportional to the final volume of concrete eroded. The initial superheat in the debris and the initial level of decay heat in the debris were considered to be unimportant to the final volume eroded.

Results of Expert F's Elicitation

The Expert verified that the thermal penetration front preceded the erosion front by no more than 5 cm. He also stated that most of the erosion that occurred above the drywell floor was due to radiation--this would not be more than 20 cm.

This Expert gave the results for erosion depth in terms of volume of concrete eroded and direction of erosion. (Maximum radial erosion would correspond to minimum axial erosion.)

The Expert defined a base case consisting of a high debris flow rate from the vessel, no water on the debris, and a large amount of zirconium available in the debris. For the base case, the Expert stated that for the purpose of source term assessment, the period of interest of the CCI would last for 8 h. At 1 h, 30% of the final erosion volume has been eroded. At 3 h, 60% of the final volume has been eroded. The Expert stated that the error in these values is $\pm 5\%$.

The Expert defined a cumulative distribution on the maximum radial erosion depth associated with the maximum volume eroded for the base case--the results are presented below:

<u>Δr (cm)</u>	<u>$F(\Delta r)$</u>
40	.05
50	.25
75	.95
110	.99
130	1.0

Δr : maximum radial erosion
 $F(\Delta r)$: CDF

Values were also given for axial erosion rates, but for this issue we are not concerned with erosion in the axial direction (the Structural Response Panel judged the axial erosion to be unimportant to the pedestal failure issue.)

The effect of water, debris pour rate from the vessel, the amount of zirconium remaining in the debris on the CCI was described by the Expert in terms of changes in the duration of the CCI or changes in the total volume eroded:

1. Effect of water--add 2.5 h to the duration of CCI (e.g., 8 h + 2.5 h = 10.5 h)--total volume eroded stays constant
2. Effect of low pour--add 40 minutes to the duration of CCI--total volume eroded stays constant
3. Effect of low zirconium--divide final erosion volume by 2--duration of CCI stays constant

Conversion of Expert's values to tabular form for aggregation

Given the maximum radial erosion depth and the percentage of volumetric erosion, the radial erosion depth was calculated using the following equation:

Equation 1:

$$\Delta r = ((V/V_{max}) * \Delta r_{max}^2)^{0.5}$$

Δr -- radial erosion depth

V -- volume eroded at time of interest

V_{max} -- volume eroded at end of CCI

V/V_{max} -- percentage of volumetric erosion at time of interest

Δr_{max} -- radial erosion depth for V_{max}

All of the operations defined by the expert to modify the base case operated on V/V_{max} or V_{max} . The values for R_{max} in Equation 1 stayed constant. The R_{max} values for the .01, .5, and .99 quantiles are given below:

Δr_{max} for .01 quantile -- 38 cm (extrapolated from values given by expert)

Δr_{max} for .5 quantile -- 58.9 cm (interpolated from values given by expert)

Δr_{max} for .99 quantile -- 110 cm

Values for V/V_{max} for the base case were modified using the Expert's instructions on how to manipulate V_{max} , V/V_{max} and the timing of CCI. V/V_{max} values for all cases defined by the Expert are presented in the table below.

Table F-1
Interpolated Values of V/V_{max} for Cases Defined by Expert
(top value: .01 quantile, middle value: .5 quantile
bottom value: .99 quantile in centimeters)

Case	1 h	3 h	6 h	10 h
Large pour, High Zirconium No water	20.8 32.3 60.3	29.4 45.6 85.2	34.8 54.0 100.8	38.0 58.9 110.0
Large pour, Low Zirconium No water	14.7 22.8 42.6	20.8 32.3 60.3	24.6 38.2 71.3	30.0 46.6 87.0
Large pour, High Zirconium Water	18.2 28.2 52.6	25.7 39.8 74.4	30.4 47.1 88.0	37.8 58.6 109.5
Large pour, Low Zirconium Water	12.9 19.9 37.2	18.2 28.2 52.6	21.5 33.3 62.2	26.7 41.4 77.4
Low pour, High Zirconium No Water	20.0 31.0 57.9	28.3 43.8 81.9	33.5 51.9 96.8	38.0 58.9 110.0
Low pour, Low Zirconium No water	14.1 21.9 40.9	20.0 31.0 57.9	23.7 36.7 68.5	28.9 44.7 83.6
Low pour, High Zirconium Water	17.6 27.3 51.0	24.9 38.6 72.1	29.5 45.7 85.4	36.3 56.2 104.9
Low pour, Low Zirconium Water	12.5 19.3 36.1	17.6 27.3 51.0	20.9 32.3 60.4	25.6 39.7 74.2

The values in the above table and the values for R_{max} for the .01, .50, and .99 quantiles were used as input to Equation 1 to calculate the radial erosion depth values for all times necessary to fill out the tables presented in aggregated results.

Sources of Uncertainty

The uncertainty in the radial erosion depth is largely due to the uncertainty in the direction of concrete erosion. This uncertainty overwhelms the uncertainty in the volume that is eroded. The Expert chose his values with only zirconium in mind. Taking other unoxidized metals into account could modify the results by 20%.

APPENDIX A

APPENDIX A

This Appendix contains lists of references provided to the Containment Loads Panel and Molten Core/Containment Interaction Panel.

LIST OF INFORMATION SUPPLIED TO CONTAINMENT LOADS PANEL

SUPPLIED AT CONTAINMENT LOADS PANEL MEETING, December 15-17, 1987

1. Welcome and Introduction, N. R. Ortiz, SNL. COPIES OF VIEWGRAPHS.
2. Elicitation of Expert Opinion, Steve Hora, University of Hawaii at Hilo. COPIES OF VIEWGRAPHS.
3. Overview of NUREG-1150 backend methodology, Fred Harper, SNL. COPIES OF VIEWGRAPHS.
4. Introduction to NUREG-1150 Containment Loading and MCCI Issues, Eric Haskin, SNL. COPIES OF VIEWGRAPHS.
5. Hydrogen Phenomena at Grand Gulf (Issue #1), Chris Amos, SAIC. COPIES OF VIEWGRAPHS.
6. Presentation of hydrogen research results, Marty Sherman, SNL. COPIES OF VIEWGRAPHS.
7. Containment Loads at Sequoyah due to Hydrogen Phenomena prior to Vessel Breach (Issue #2), J. J. Gregory, SNL. COPIES OF VIEWGRAPHS.
8. BWR Reactor Building Failure Due to Hydrogen Burns (Issues #3&4), Arthur C. Payne, Jr., SNL. COPIES OF VIEWGRAPHS.
9. Pressure Rise at Vessel Breach at Grand Gulf (Issue #5), C. N. Amos, SAIC. COPIES OF VIEWGRAPHS.
10. Fuel-Coolant Interactions, Marshall Berman, SNL. COPIES OF VIEWGRAPHS.
11. An Experimental Study of Isothermal and Boiling Liquid Jets, B. W. Marshall, Jr. and M. Berman, 14th Water Reactor Safety Research Information Meeting, Gaithersburg, Maryland, October 27-31, 1986. COPIES OF VIEWGRAPHS.
12. Ex-Vessel FCIs for Grand Gulf Risk Analysis, Marshall Berman (Memo to Allan Benjamin, December 19, 1986.)
13. Melt-Coolant Interactions Sandia/NRC Bibliography, July 8, 1987.
14. Pressure Rise at Vessel Breach for PWRs (Issues #8-10), Walter B. Murfin, Technadyne. COPIES OF VIEWGRAPHS.
15. Letter to Elaine D. Bergeron from Chang K. Park, December 14, 1987. This letter outlines the differences between Zion and other plants that might be important to Issue #10.
16. "Pressure-Temperature Response in an Ice-Condenser Containment for Selected Accidents", S. E. Dingman and A. L. Camp, SAND85-1824C (Sandia National Laboratories, Albuquerque, NM).
17. "Pressurized Melt Ejection into Scaled Reactor Cavities", W. Tarbell, M. Pilch, J. Brockmann, J. Ross, D. Gilbert, NUREG/CR-4512, SAND86-0153, October 1986.
18. "High Pressure Ejection of Melt from a Reactor Pressure Vessel: The Discharge Phase", M. Pilch and W. Tarbell, NUREG/CR-4183, SAND85-0012, September 1985.
19. "Surry S2D Severe Accident Containment Loads Calculations Using HMC", L. Pong, M. Corradini, G. Moses, UWRSR-34 (University of Wisconsin, Madison, WI), March 1986.
20. "High-Pressure Melt Ejection", T. M. Lee (from Uncertainty Papers on Severe Accident Source Terms, NUREG-1265, Chapter 4).
21. Combustion-Induced Loads in Large-Dry PWR Containments, F. E. Haskin, V. Behr and L. Smith (In Proceedings of the Second

- Workshop on Containment Integrity", T. Molina and R. Cochrell, eds., NUREG/CP-0056, SAND84-1514, pages 129-162.
22. "Preliminary Calculations on Direct Heating of a Containment Atmosphere by Airborne Core Debris", M. Pilch and W. Tarbell, NUREG/CR-4455, SAND85-2439, July 1986.
23. "Hydrodynamics Aspects of Ex-Vessel Debris Dispersal in Zion-type Containment Design", B. Spencer, D. Kilsdonk and J. Sienicki, ANL/LWR/SAF 83-1, January 1983.
24. "Corium Droplet Size in Direct Containment Heating", J. Sienicki and B. Spencer, in Severe-Accident Therman Hydraulics, pp. 557-564.
25. "Results from the DCH-1 Experiment", W. Tarbell, J. Brockmann, M. Pilch, J. Ross, M. Oliver, D. Lucero, T. Kerley, F. Arellano, R. Gomez, NUREG/CR-4871, SAND86-2483, June 1987.
26. "Steam Explosion Experiments at Intermediate Scale: FITSB Series", D. Mitchell and N. Evans, NUREG/CR-3983, SAND83-1057, February 1986.
27. "High Pressure Melt Ejection and Direct Containment Heating in Ice Condenser Containments", M. Pilch, W. Tarbell, D. Carroll and J. Tills, Presented at the International ANS/ENS Topical Meeting on Operability of Nuclear Power Systems in Normal and Adverse Environments, October 1, 1986.
28. DCH Experiments and Analyses at Sandia National Laboratories, W. Tarbell, M. Pilch, J. Brockmann, SNL. COPIES OF VIEWGRAPHS.
29. Aspects of Zion-specific DCH Loading Phenomenology, T. Ginsberg, BNL. COPIES OF VIEWGRAPHS.
30. CONTAIN DCH Calculations for PWRs, D. Williams, K. Bergeron, D. Carroll, D. Louie, K. Murata, J. Tills, K. Washington, SNL. COPIES OF VIEWGRAPHS.
31. "Containment Loads due to Direct Containment Heating and Associated Hydrogen Behavior: Analysis and Calculations with the CONTAIN Code", D. Williams, K. Bergeron, D. Carroll, R. Gasser, J. Tills and K. Washington, NUREG/CR-4896, SAND87-0633, May 1987.
32. Statements on Containment Loading and Hydrogen Issues at Sequoyah, W. Lau, TVA.
33. "MARCH-HECTR Analysis of Selected Accidents in an Ice-Condenser Containment", A. Camp, V. Behr and F. Haskin, NUREG/CR-3912, SAND83-0501, December 1984.
34. Draft of "Technical Report 23.1, Sequoyah Nuclear Plant, Integrated Containment Analysis" (Tennessee Valley Authority, Knoxville, Tennessee), July 1984.

LIST OF DOCUMENTS MAILED TO CONTAINMENT LOADS PANEL AFTER DECEMBER MEETING

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36. "Direct Heating" (List of references compiled by the USNRC for use by expert panels).
37. DCH in Integrated Accident Analysis Using MAAP 3B, Marc Kenton, FAI. COPIES OF VIEWGRAPHS.
38. Direct Containment Heating, F. Torri, PL&G. COPIES OF VIEWGRAPHS.

39. "Update on CONTAIN DCH Calculations for Surry", D. C. Williams (Memo to NUREG-1150 Containment Loads Panel, January 11, 1988).
40. "Parametric CONTAIN Calculations of the Containment Response of the Grand Gulf Plant Due to Reactor Pressure Vessel Failure at High Pressure", K. K. Murata and D. L. Y. Louie, SNL (Attachment to a Memo from K. Murata to the NUREG-1150 Expert Panel Members, February 15, 1988).
41. "Possibility of Ignition of H₂", J. H. S. Lee (Memo to Containment Loads Panel members, February 16, 1988).
42. "Elicitation Meeting March 7-11", Roger Breeding (Memo to Containment Loads Panel, March 1, 1988).
43. "Transient Therman Hydraulic Analysis of Reactor Coolant System During Station Blackout Sequences" (From PLG-0550, pp. 6-1 to 6-57), July 1987.
44. "Phenomenological Uncertainties", (From PLG-0550, pp. 8-29 to 8-99), July 1987.
45. "Explosions of Molten Aluminum in Water- Cause and Prevention", George Long, Metal Progress, 71, 107 (1957).
46. "Summary Report, Information for Consideration with Mark III Detonation Issue" (Letter report mailed to E. Bergeron by J. R. Langley, January 5, 1988).
47. Draft of "Report Assessing the Ability of Mark III Containments to Support Detonations" (Letter report mailed to E. Bergeron by J. R. Langley, January 5, 1988).

MAILED ONLY TO MEMBERS OF PANEL CONSIDERING ISSUES 3&4

48. Reactor Building Burn Calculations, S. Dingman, SNL. COPIES OF VIEWGRAPHS.
49. "MELCOR and HECTR Calculations for Peach Bottom Reactor Building", S. Dingman and F. Haskin, COPIES OF VIEWGRAPHS of presentation at Silver Springs, MD, April 29, 1986.
50. Letter report to Tom Walker, USNRC from E. Haskin, SNL, May 21, 1986.
51. "Analysis of Peach Bottom Station Blackout with MELCOR", S. Dingman, R. Cole, F. E. Haskin, SAND86-2129C.
52. "Model Description for ORNL Nine Cell Peach Bottom Secondary Containment Model - PB.9.SC.1", Sherrell Greene (Letter Report sent to Jeremy L. Sprung, SNL by Sherrell Greene, November 10, 1986).
53. "The Role of BWR MK I Secondary Containments in Severe Accident Mitigation", Sherrell R. Greene, Proceedings of the 14th Water Reactor Safety Information Meeting, Gaithersburg, Maryland, October 27-31, 1986.
54. "The Impact of BWR MK I Primary Containment Failure Dynamics on Secondary Containment Integrity", Sherrell Greene, Proceedings of the 15th Water Reactor Safety Information Meeting, Gaithersburg, Maryland, October 29, 1987.
55. "Uncertainties in Hydrogen Combustion, D. Stamps, C. Wong and L. Nelson, SAND87-2277C, October 1987.
56. "HECTR Analyses of the Nevada Test Site (NTS) Premixed Combustion Experiments", C. Wong, To be Published, 1987.
57. Results of Lasalle blowdown calculations.

58. "Rise and Fall of the Sequoyah ABNBY Plant Damage State", D. C. Williams (Memo to Distribution, December 11, 1987).
59. "CONTAIN Calculations for Some DCH Scenarios in the Sequoyah Plant", D. C. Williams (Letter Report to the NUREG-1150 Source Term and Loads Panels, April 5, 1988)
60. "An Update on Direct Containment Heating for Ice Condenser Plants", J. Tills (Informal Transmission to NUREG-1150 Containment Loads Expert Panel, January 12, 1988).
61. "Possibility of Detonation and Other Containment Loads for Sequoyah", M. Sherman, February 23, 1988.
62. "Grand Gulf Hydrogen Deflagration and Detonation Loads Prior to Vessel Breach", M. Sherman, March 1, 1988.
63. "Vapor Explosions in the BWR Mark II Wetwell", M. Corradini (Attachment to Letter to E. Bergeron, January 20, 1988).
64. "Stratified Vapor Explosion Experiments", K. Bang and M. Corradini (Conference paper to be presented at the national Heat Transfer Conference, Houston, Texas, August 1988).
65. "Ex-Vessel FCI in a Mark-III Drywell", M. Corradini (Attachment to Letter to E. Bergeron, January 2, 1988).

MAILED TO PANEL BY T. GINSBERG

66. "Contain Sensitivity Calculations of Zion DCH Containment Loadings", T. Ginsberg, C. Grimshaw, C. Park, N. Tutu (Letter report, February 26, 1988)

★

SUPPLIED AT CONTAINMENT LOADS PANEL ELICITATION MEETING, MARCH 8-11, 1988

67. QUASAR results (Attachment to Letter to Dr. Patricia Worthington, USNRC from Min Lee, BNL, March 7, 1988)
68. Hydrogen Phenomena at Grand Gulf (Issue #1), C. Amos, SAIC. COPIES OF VIEWGRAPHS.
69. Grand Gulf Hydrogen Burn Calculations, Tom Brown. COPIES OF VIEWGRAPHS.
70. HECTR Grand Gulf Calculations, T. Brown, SNL. COPIES OF VIEWGRAPHS.
71. Perspective on Issue #1, J. Metcalfe, S&W. NOTES. 83. Perspective on Issue #1, L. Baker, ANL. NOTES.
72. Grand Gulf Hydrogen Deflagration and Detonation Loads Prior to Vessel Breach, March 1, 1988. M. Sherman, ANL.
73. Containment Loads at Sequoyah due to Hydrogen phenomena prior to vessel breach (Issue #2), J. J. Gregory, SNL. COPIES OF VIEWGRAPHS.
74. Perspective on Issue #2, J. Melcalfe, S&W. NOTES.
75. Perspective on Issue #2, P. Worthington, NRC. NOTES.
76. Lasalle MELCOR hydrogen calculations, Arthur Payne, SNL. COPIES OF VIEWGRAPHS.
77. Perspective on Issues 3&4, Marty Plys, FAI. NOTES.
78. Perspective on Issues 3&4, Fred Torri, PL&G. NOTES.
79. Pressure Rise at Vessel Breach at Grand Gulf (Issue #5), C. Amos, SAIC. COPIES OF VIEWGRAPHS.
- *80. Description of recent CONTAIN Calculations for Grand Gulf, K. Murata, SNL. COPIES OF VIEWGRAPHS.

81. Perspective on Issue #5, K. Bergeron, SNL. NOTES.
82. Perspective on Issue #5, T. Ginsberg, BNL. NOTES.
83. Perspective on Issue #5, L. Baker, ANL. NOTES.
84. Perspective on Issue #8, Marty Plys, FAI. NOTES.
85. Perspective on Issue #8, K. Bergeron, SNL. NOTES.
86. Perspective on Issue #8, T. Ginsberg, SNL. NOTES.
87. Pressure Increment at Vessel Breach for Surry, Walt Murfin,.
COPIES OF VIEWGRAPHS.
88. Pressure Increment at Vessel Breach for Zion (Issue #10), W.
Murfin, Technadyne. COPIES OF VIEWGRAPHS.
89. Perspective on Issue #10, Marty Plys, FAI. NOTES.
90. Perspective on Issue #10, Fred Torri, PL&G. NOTES.
91. Perspective on Issue #10?????, Ted Ginsberg, BNL. NOTES.

**LIST OF HANDOUTS GIVEN TO MOLTEN-CORE CONTAINMENT EXPERT PANEL
(6-21-88)**

1. Welcome and Introduction, N. R. Ortiz, SNL. COPIES OF VIEWGRAPHS.
2. Elicitation of Expert Opinion, Steve Hora, University of Hawaii at Hilo. COPIES OF VIEWGRAPHS.
3. Overview of NUREG-1150 backend methodology, Fred Harper, SNL. COPIES OF VIEWGRAPHS.
4. Introduction to NUREG-1150 Containment Loading and MCCI Issues, Eric Haskin, SNL. COPIES OF VIEWGRAPHS.
5. Pedestal Erosion at Grand Gulf, Thomas D. Brown, SNL. COPIES OF VIEWGRAPHS.
6. Core-Concrete Interactions, E. R. Copus. COPIES OF VIEWGRAPHS.
7. Reactor Cavity Floor Failure at LaSalle, Arthur C. Payne, Jr. COPIES OF VIEWGRAPHS.
8. "Miscellaneous Calculations", Arthur C. Payne Jr. and Clint J. Shaffer, SNL. HANDOUT.
9. Hand Calculations for Concrete Attack and Pedestal Failure Timing Applications to LaSalle and Grand Gulf, Martin G. Plys. COPIES OF VIEWGRAPHS.
10. Peach Bottom Drywell Meltthrough Issue, Fred T. Harper. COPIES OF VIEWGRAPHS.
11. Review of the Status of the Mark I BWR Steel Containment Shell Melt-Through Analyses, G. A. Greene. COPIES OF VIEWGRAPHS.
12. Mark I Liner Temperature Response Calculations, Mike Epstien. COPIES OF VIEWGRAPHS.
13. BWR Mark I Containment Shell Melt Through Analyses, T. Walker. COPIES OF VIEWGRAPHS.

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14. "The Jet Impingement Phase of Molten Core-Concrete Interactions", J. J. Sienicki and B. W. Spencer, Proceedings of the Committee on the Safety of Nuclear Installations (CSNI) Specialists' Meeting on Core Debris-Concrete Interactions, February 1987.
15. "Concrete Data for Primary Containment", George Crane, attachment to letter to Arthur Payne, 11 February 1987.
16. "Large-Scale, Transient Tests of the Interaction of Molten Steel with Concrete", Dana Powers and Frank Arellano, NUREG/CR-2282, SAND81-1753.
17. "Hydrodynamics and Heat Transfer Aspects of Corium-Water Interactions", Interim Report, B. Spencer, J. Sienicki and L. McUmber, EPRI NP-5127, March 1987 (Electric Power Research Institute)
18. Inside NRC, Vol 9, No. 25, Dec 7, 1987.
19. D. A. Powers, and F. E. Arellano, Erosion of Steel Structures by High Temperature Melts NUREG/CR-2284, SAND81-1755, Sandia National Laboratories, Albuquerque, NM, June, 1983.
20. D. A. Powers, Erosion of Steel Structures by High Temperature Melts, Nuclear Science and Engineering 88 (1984) 357

21. D. A. Powers and F. E. Arellano, High Temperature Melt Attack on Steel and Urania-Coated Steel, NUREG/CR-3366, SAND83-1350, Sandia National Laboratories, Albuquerque, NM, April, 1984.
22. G. A. Greene, K. R. Perkins, and S. A. Hodge, "Mark I Containment Drywell, Impact of Core/Concrete Interactions on Containment Integrity and Failure of the Drywell Liner" in Source Term Evaluation for Accident Conditions IAEA, Vienna, Austria, paper IAEA-SM-281/36 page 429, Oct. 26-Nov. 1, 1985.
23. "Appendix D -- Estimates of the Containment Ultimate Pressure Capacity and the Failure Modes, IDCOR 85.3-B2, FAI-86-1 (document numbers may not be correct -- I only have copy of the appendix.)
24. Letter from A. R. Buhl, IT to Eric S. Beckjord, NRC, July 9, 1987, Response to Brookhaven National Laboratory's (BNL) Comments on IDCOR's Model of the Mark I Containment Response to Direct Contact with Molten Core Debris.
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