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Simplified Containment Event Tree Analysis for the Sequoyah Ice Condenser Containment

Prepared by
W. J. Galyean, J. A. Schroeder, D. J. Pafford

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ABSTRACT

An evaluation of a Pressurized Water Reactor (PWR) ice condenser containment was performed. In this evaluation, simplified containment event trees (SCETs) were developed that utilized the vast storehouse of information generated by the NRC's Draft NUREG–1150 effort. Specifically, the computer programs and data files produced by the NUREG–1150 analysis of Sequoyah were used to electronically generate SCETs, as opposed to the NUREG–1150 accident progression event trees (APETs). This simplification was performed to allow graphic depiction of the SCETs in typical event tree format, which facilitates their understanding and use. SCETs were developed for five of the seven plant damage state groups (PDSGs) identified by the NUREG–1150 analyses, which includes: both short– and long–term station blackout sequences (SBOs), transients, loss–of–coolant accidents (LOCAs), and anticipated transient without scram (ATWS). Steam generator tube rupture (SGTR) and event–V PDSGs were not analyzed because of their containment bypass nature. After being benchmarked with the APETs, in terms of containment failure mode and risk, the SCETs were used to evaluate a number of potential containment modifications. The modifications were examined for their potential to mitigate or prevent containment failure from hydrogen burns or direct impingement on the containment by the core, (both factors identified as significant contributors to risk in the NUREG–1150 Sequoyah analysis). However, because of the relatively low baseline risk postulated for Sequoyah (i.e., 12 person–rems per reactor year), none of the potential modifications appear to be cost effective.

FIN No. A6900—PWR Ice Condenser Containment Venting/Enhancements

EXECUTIVE SUMMARY

As presented in draft NUREG–1150, the analysis of the Sequoyah Nuclear Power Plant with an Ice–condenser containment yielded the identification of seven risk important plant damage states (PDS). These PDSs are identified as:

PDS–1	slow or long–term station blackout (SBO–LT)
PDS–2	fast or short–term station blackout (SBO–ST)
PDS–3	the occurrence of a loss–of–coolant accident (LOCA)
PDS–4	event–V sequence
PDS–5	transients
PDS–6	anticipated transient without scram (ATWS)
PDS–7	steam generator tube rupture (SGTR).

Of the seven, two are containment bypass sequences (event–V and SGTR). Because of their containment bypass nature, these two are not included in the present analysis.

Simplified containment event tree (SCET) methodology has been applied to the NUREG–1150 Sequoyah APET models for each of the five PDSs in which risk is influenced by containment performance. These SCETs were developed utilizing the APETs as the basis for determining both event dependencies and probabilities. Furthermore, the SCET results were benchmarked against those produced by the APETs. Generally, very good agreement was achieved between the SCET and the APET results for the containment failure mode results (i.e., conditional containment failure probabilities). However, only a satisfactory match was achieved on the risk results. Most likely, a further refinement of the source term binning (i.e., the procedure for generating the 14–character source term vector) would yield more precise results.

Once the SCETs were available, they were used to assess the benefit associated with a number of potential containment improvements, which included (a) backup power to the hydrogen igniter system, (b) backup power to the igniters and to the containment air recirculation fan system, (c) mitigation of direct impingement containment failures, and (d) hydrogen control through the inerting of the containment atmosphere.

None of the potential containment modifications appear to be cost effective in reducing the risk for Sequoyah. This is best illustrated through the use of a bounding calculation that shows a total of $480,000 would be justifiable for backfits provided, 100% of the population dose risk (12 person–rem per reactor year) could be averted and assuming the plant life expectancy is 40 years.

FOREWORD

SECY-88-147, dated May 25, 1988, presented the NRC staff's program plan to evaluate generic severe accident containment vulnerabilities via the Containment Performance Improvement Program (CPIP). This effort was predicated on the presumption that there are generic severe accident challenges for each light water reactor (LWR) containment type that should be addressed to determine whether additional regulatory guidance or requirements concerning needed containment features are warranted, and to confirm the adequency of the existing Commission policy. These challenges should be addressed to determine the possible need for additional regulatory guidance or requirements related to containment features. The ability of containments to successfully survive some severe accident challenges is uncertain, as indicated in Draft NUREG-1150. The CPI effort is intended to focus on evaluation of hardware and procedural issues related to generic containment challenges.

This report documents the results of NRC-sponsored research related to severe accident challenges and potential enhancements that could improve containment performance. The purpose of this report is to provide PWR Ice Condenser owners with information they may find useful in assessing their plants as part of their Individual Plant Examination (IPE) program. No requirements are contained in this report and it is being provided for information only. Specific guidance to the industry on the use of this report, and similar reports has been given in Generic Letter 88-20, Supplement 3, dated July 6, 1990.

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TABLES

ACRONYMS

APET	Accident Progression Event Tree
ARF	Air Return Fans
ATWS	Anticipated Transient Without Scram
BMT	Basemat Melt–Through
CCI	Core–Concrete Interaction
CF	Chronic Fatalities
CPI	Containment Performance Improvement
CPIP	Containment Performance Improvement Program
DCH	Direct Containment Heating
EF	Early Fatalities
EVSE	Ex–vessel Steam Explosion
HPME	High Pressure Melt Ejection
IVSE	In–vessel Steam Explosion
LOCA	Loss–of–Coolant Accident
LOSP	Loss of Offsite Power
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PDS	Plant Damage State
PDSG	Plant Damage State Group
PORV	Power Operated Relief Valve
PRA	Probabilistic Risk Assessment
PSIA	Pounds per Square Inch Absolute
RCS	Reactor Coolant System
RWST	Refueling Water Storage Tank
SBO	Station Blackout
SCET	Simplified Containment Event Tree
SG	Steam Generator
SGTR	Steam Generator Tube Rupture
SNL	Sandia National Laboratory
SRV	Safety Relief Valve
VB	Vessel Breach

SIMPLIFIED CONTAINMENT EVENT TREE ANALYSIS FOR THE SEQUOYAH ICE CONDENSER CONTAINMENT

1. INTRODUCTION

Because of the concern about the ability of nuclear power plant (NPP) containments to survive the effects of possible severe accidents, the NRC initiated a program to evaluate the vulnerability of the various containment types to the challenges posed by possible severe accidents. This program, entitled the Containment Performance Improvement Program (CPIP), examines each of the containment types found at U.S. NPPs. This report documents work performed in support of the evaluation of the Ice Condenser containment type.

The analysis described in this report draws heavily from the NRC analysis of severe accident risks documented in Draft NUREG-1150. NUREG-1150 represents a state-of-the-art understanding of severe accident phenomenology as it existed in 1988. It provides a catalog of risk significant accident scenarios and containment events, and is intended to provide a testbed for the evaluation of risk-reduction measures. However, NUREG-1150 is a result of a level of effort that cannot easily be duplicated. Furthermore, the methods and data used in 1150 are not completely documented one year from the publication of the main report. This makes it less likely that utilities will use the full 1150 methodology in their individual plant examinations. Therefore, this analysis has two goals: (a) to utilize the understanding gained through the 1150 research to evaluate the risk reduction potential of possible containment improvements and (b) to provide a less complicated framework for the analysis of ice condenser containments. The purpose of this simplified framework, is to provide utilities with a containment analysis option that could be implemented in the individual plant examination process, which has its roots in the NUREG-1150 knowledge base.

For the evaluation of potential ice condenser containment improvements, the CPIP has produced a document entitled "An Assessment of Ice-Condenser Containment Performance Issues."[1] This document identifies several improvements thought to have the potential for cost effective reduction in the risk resulting from severe accidents. These improvements include: (a) an improved hydrogen igniter system, (b) manual RCS depressurization, (c) enhancement of the air return fans, (d) enhancement of the containment spray system, (e) reactor cavity flooding, (f) core debris control, (g) filtered containment venting, and (h) containment inerting. Various aspects of these items have already been addressed using the full weight of the 1150 methodology.[2] This report focuses on providing backup power to the hydrogen igniters, backup power to both the igniters and fans, prevention of direct impingement failures, and containment inerting.

The benefit of these improvements is determined using the SCETs developed for this project, with the exception of the backup power to igniters and fans improvement, which is evaluated using the detailed APETs from the 1150 analysis of Sequoyah. The SCETs are developed utilizing the APETs created in 1150. The methodology used to construct the SCETs is outlined in Section 2 of this report. Section 3 describes the preliminary steps required before SCET development can begin, namely verifying the integrity of the 1150 computer codes and data files. Section 4 then provides details of SCET construction for five of the seven plant damage state classes or groups identified in the 1150 analysis. The excluded groups involve bypass scenarios that would not be affected by the aforementioned containment improvements. The groups analyzed include both short- and long-term station blackout, LOCA, transients, and ATWS. The SCETs developed for each plant damage state group are then used in Section 5 to evaluate the risk reduction achievable with the candidate improvements. The SCETs were not developed in sufficient detail to evaluate an improvement consisting of backup power to both igniters and fans (the effect of the containment air recirculation fans is not explicitly modeled it the SCETs). Therefore, this improvement was evaluated directly with the 1150 APETs.

It should be noted that the SCETs developed for this analysis are a condensed version of the 1150 APETs, and not an independent construction as was provided in the Mark I CPI analysis.[3] They are developed directly from the 1150 data. The results of the base case containment failure mode and risk predictions obtained with the SCETs have been benchmarked against the results obtained with the 1150 APETs, and generally display good agreement with published results.

2. SCET DEVELOPMENT METHODOLOGY

The method of analyzing containment response developed for Draft NUREG-1150 involves the use of large APETs. These trees typically have a hundred or more events, each comprising several branches or options. Consequently, the resulting event trees are too large for graphical representation, and the endstates are so numerous they are incomprehensible without computer-based reduction. These factors make understanding the possibilities described by the tree extremely difficult. Furthermore, the NUREG-1150 APETs require significant computer resources to process, making detailed sensitivity studies prohibitively expensive. The advantage of the APET methodology is that it produces a model, complete with an uncertainty estimate, of the current knowledge of severe accident progression phenomenology. What is needed is a way to access this phenomenological data base that suppresses many of the details, yet provides sufficient information to understand the risk significant containment events that result.

The analysis described in this report relies mainly on SCETs to evaluate potential containment improvements and provide a framework for understanding the Draft NUREG-1150 analyses. Because SCETs are limited to 10-20 top events and at most a few hundred endstates, it is possible to graphically display them. These event trees, while still large, can be understood without computer-based reduction. When properly benchmarked, the SCETs can reproduce many of the results obtained with the full APETs. However, information is lost when extracting the SCETs from the APET data base. In most cases this is not significant.

Once developed and benchmarked, the SCETs can be used to perform sensitivity studies on the value of potential containment improvements. While not capable of duplicating results stemming from some of the more subtle interactions modeled in the APETs, the results from these sensitivities will generally illustrate what containment response can be expected from a given improvement. Also, sensitivities can be performed using personal computer software. Specifically, ETA-II,[4] and Lotus 1-2-3.[5] This allows for fast and inexpensive treatment of sensitivities, and provides results in a form significantly more scrutable than could be obtained with the more detailed APETs. The following sections describe the codes, data, and procedures used to extract the SCETs from the APET data base.

2.1 Initial Checkout of the Draft NUREG-1150 Codes and Data

Development of SCETs requires the use of the codes and data files used in the Draft NUREG-1150 analyses. Many of the NUREG-1150 level-2 codes do not yet have user manuals, and of those that do, some are draft versions that do not necessarily reflect what is in the working version of the code. Similarly, most of the data used in the analysis exists on magnetic media and is not documented. Furthermore, the complexity of the data transfers required to ensure proper information flow from one code to another makes proper use of these codes very difficult for the uninitiated. These factors make verification of calculated results extremely important. In this analysis, verification of the codes and data was achieved through the establishment of a base case calculation that could be benchmarked against published data.

The codes used in the development of the SCETs are principally EVNTRE,[6] PSTEVNT,[7] SEQSCR,[8] PARTITION,[9] and a number of undocumented translator codes. The relationship of these codes to each other and their data flow requirements is shown schematically in Figure 1. Essentially, it is necessary to recalculate the entire back end (level 2 and level 3) analysis to verify that all data files are intact and all codes are correctly used.

The checkout process begins with the EVNTRE code, which is used to evaluate the APET. EVNTRE is a generalized event tree

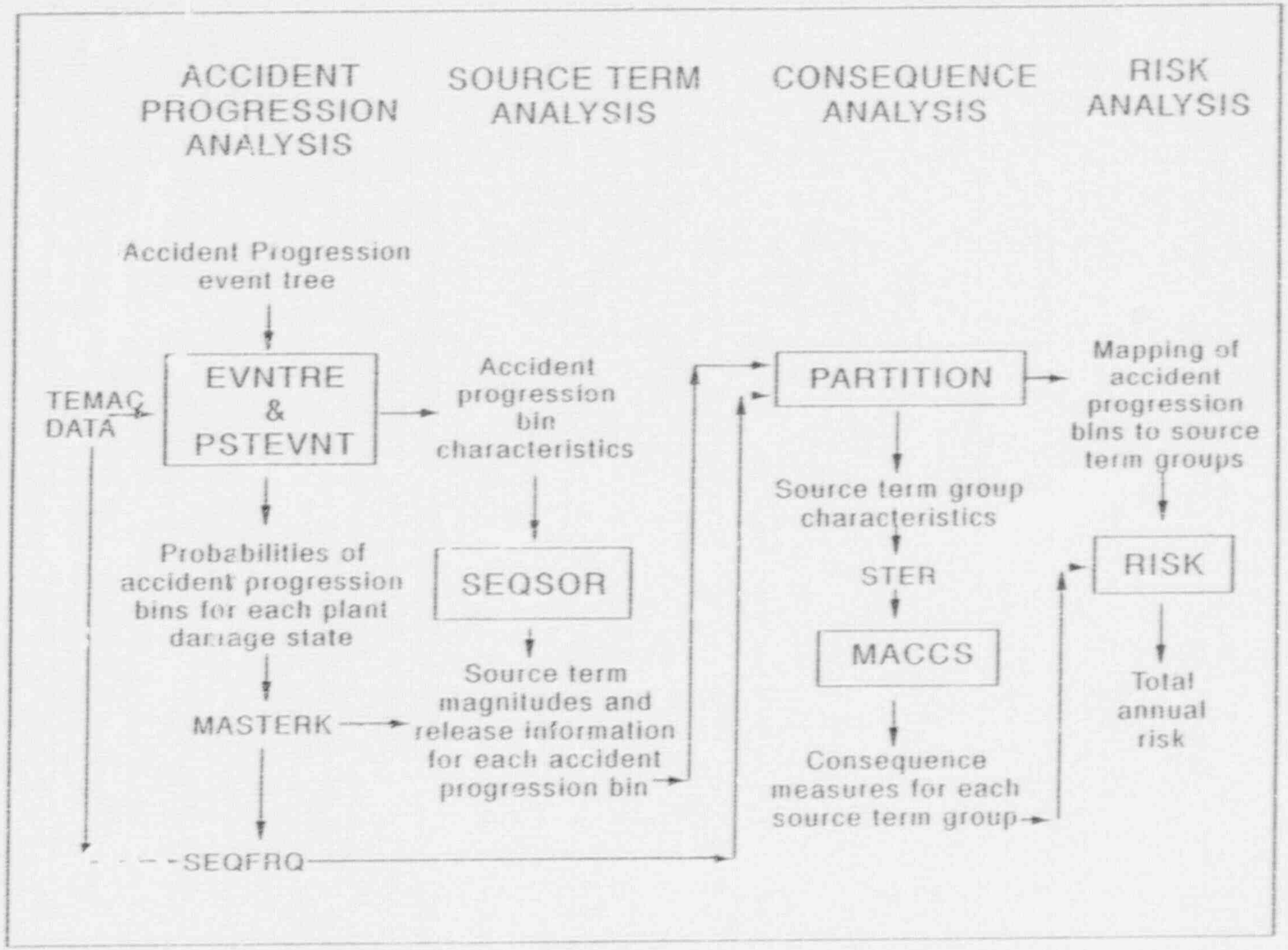


Figure 1. NUREG–1150 PRA code relationships and data flow requirements.

processor capable of evaluating very large trees. It was developed so that individual parameters could be tracked and manipulated with user-defined functions and procedures. This was necessary to evaluate the uncertainties involved in the complex phenomena occurring during severe accidents. However, a typical EVNTRE run for a single plant damage state group can take 24 hours on a workstation (e.g., an Apollo 3500), and even longer on a personal computer. Features are provided to save EVNTRE results for later processing with a faster running post processor called PSTEVNT. The process of saving the EVNTRE output for later evaluation is called accident progression binning. The results from an EVNTRE run cannot be verified against published results, so the first verification occurs after the accident progression bins are reduced to containment failure modes using the PSTEVNT code.

The PSTEVNT code is used both to reduce the accident progression bins to containment failure modes, and separately, to reduce the accident progression bins to source term bins. The output from the containment failure mode reduction step is the first fully verifiable data produced in the analysis. That is, all data produced by this step can be checked against published results. The output from the source term reduction step is passed to the parametric source term code SEQSOR.

SEQSOR generates source term release information for each of the source term bins passed from the PSTEVNT code. The calculations in SEQSOR are based on parametric representations of more detailed mechanistic accident progression calculations (e.g., Source Term Code Package or STCP). The code is also capable of representing uncertainties in key source term issues. The source term release information includes the number of release plumes, the time of release, the duration of release, the energy of the release, the height of release, and the source term release fractions for each plume. Direct computation of consequences for each of the many source terms generated by SEQSOR would require excessive computer resources, therefore the SEQSOR output is passed on to a reduction code called PARTITION.

PARTITION identifies an early and chronic fatality weight for each source term generated by the SEQSOR program. It can optionally provide a summary of these fatality weights over all the releases, or continue with the reduction by locating each release on a two-dimensional plot of the early fatality weight (EF) versus the chronic fatality weight (CF). If the summary is requested, it can be used to verify that the correct risk potential has been calculated. If the reduction is requested, PARTITION divides the fatality space into a user-specified number of cells and calculates a frequency weighted average source term for each cell. PARTITION also divides the releases identified with each cell into subgroups based upon the time of the releases relative to the evacuation start time. The output from PARTITION includes the averaged source term release information for each source term group (cell) and subgroup. This information, after some additional formatting, is used in the MELCOR Accident Consequence Code System (MACCS) analysis.[10]

The offsite consequences associated with each source term group are calculated using MACCS. MACCS input decks provide the required site and meteorological data, emergency response information, dose data, and other relevant information. The MACCS consequence information is the last data input required to complete the risk calculation. After assembly in a risk matrix (e.g., utilizing Lotus 1–2–3), the final risk numbers can be verified by comparison with published results.

To summarize, risk calculations using the NUREG–1150 computer codes and data can only be verified at three points in the process illustrated in Figure 1. These points are (a) after the calculation of reduced containment failure bin probabilities, (b) after calculation of the fatality potential summary, and (c) after calculation of the final risk numbers. Verification of calculated results at these three points is felt to provide adequate assurance that the codes have been properly installed, are being used correctly, and that the correct data are being used. At completion of these checks the code system is ready for use in developing the SCETs.

2.2 Development of the SCETs for Each PDSG

Development of the SCETs starts with definition of the important phenomena and containment failure modes. Much of this information is summarized in the NUREG/CR-4551 report on Sequoyah[2] and/or the issues characterization report.[1] Once the critical issues are identified, the APET is reviewed to determine if summary events have been defined for these issues. This should be the case for most SCET top events, although some of the top events will have to consist of combinations of existing APET events. A binner file is then created that characterizes the APET endstates in terms of the desired SCET top events.

Extraction of the SCET requires an EVNTRE evaluation of the APET utilizing the above binning definition file. The EVNTRE post processor output file contains all the reduced APET endstates and is used to define the SCET for the current plant damage state group. The information is stored by LHS[a] observation and requires additional processing to complete the SCET formation. Creation of the SCETs requires additional post-processing of the APET results, which is performed using PSTEVNT. First, the by-observation data from EVNTRE is rebinned to form an aggregated collection of endstates reflecting the mean response of the APET. This mean APET response is different than would be obtained by evaluating the APET in the point estimate mode because it includes the possibility of containment events that only occur when samples are taken from the tails of the uncertainty distributions. Next, the SCET endstate identifiers and frequencies are stripped from the PSTEVNT aggregated output and are reformatted to create a new PSTEVNT input file. This new input file of the mean response is sorted by top events, using the sort feature of PSTEVNT, to create the SCET in its final form.

The sorted output from PSTEVNT is next loaded into the ETA-II pc-based event tree graphics program.[4] The PSTEVNT output is converted from ASCII text file into ETA-II data file format using ETLOAD software.[11] Once loaded into ETA-II, the SCET can be displayed graphically. Benchmarking of the SCET by containment failure mode is done at this point.

2.3 Development of Containment Failure Mode Binning

The SCET development described in the preceding section results in few enough endstates that accident progression binning is not required prior to obtaining containment failure mode results. Containment failure mode probabilities are obtained by manually applying the binning process described in Section 2.4.3 of Reference 2. This is easily done using an ETA-II feature that totals sequence frequencies over user defined containment failure mode end states. For this analysis, the SCETs are initially benchmarked against the presentation bins provided in Figure 5.3 of Draft NUREG-1150.[12] By benchmarking the SCET at this point, it is possible to verify that the choice of top events is adequate to represent the significant containment failure modes. Benchmarking of the SCETs by risk and risk potential is also required and is discussed in Section 2.4.

2.4 Risk Development

Development of risk information for the SCET endstates requires additional analysis using the NUREG-1150 tools and models. The process starts with the creation of a new PSTEVNT rebinning definition file. The new rebinner groups the SCET endstates in accordance with the source term binning scheme used in the 1150 analyses. Fourteen characteristics are used with each characteristic having several dimensions. Because the SCET contains only a fraction of the information contained in the APET, a number of approximations and simplifications are required to define

a. LHS refers to the limited Latin Hypercube Sampling technique used by the NUREG-1150 effort to generate uncertainty distributions for the risk results.

some of the source term characteristics. The PSTEVNT output from this evaluation is passed to the SEQSOR program to parametrically assign the source term release information for each of the source term bins. At this step of the analysis, the sampling capabilities of the SEQSOR program are not used. Only the central estimates for distributed parameters are used. For the PDSs analyzed here, 400–500 source terms result from the binning process. Reduction of the number of source terms to a more manageable level is obtained using the PARTITION code. For the SCETs developed in this analysis, the number of source terms was reduced to 17. Consequence estimates are then obtained for these 17 source terms, using the MACCS code. Annual risk is calculated by combining the consequence estimates with the release group frequencies using a Lotus 1-2-3 worksheet. Benchmarking the SCETs at the final risk calculation is performed to establish a base case.

3. DEVELOPMENT OF A BASE CASE

The following sections describe the base case calculation made to verify code use and data flow as discussed in Section 2.1. The data files used in this analysis were originally constructed by Sandia National Laboratory (SNL) for the Sequoyah NUREG-1150 analysis. The computer codes and data used in this analysis were obtained directly from SNL. Others wishing access to the computer codes, models, and data used in this analysis should send a formal request for the complete suite of level-2 and level-3 PRA codes, and the Sequoyah data files to the Director, Division of Systems Research, Office of Nuclear Regulatory Research, USNRC, Washington, D.C. 20555. Current plans call for revision of these codes by SNL, and for future distribution through the National Energy Software Center at the Argonne National Laboratory in Argonne, Illinois.

3.1 Base Case Scope

The results of the base case calculations are presented for three points in the process; containment failure mode probabilities (presentation bins), risk potential, and risk. The presentation bins are a summary of the APET endstates in terms of containment failure mode. Risk potential is a summary output produced by PARTITION, which estimates the potential fatalities resulting from the combined containment failure source terms. The risk results are calculated using consequences generated by the MACCS code.

The base case calculation begins at core damage. Information from the core damage analysis[13] is passed to the level-2 analysis in the form of TEMAC output.[14] These data list core damage frequency by plant damage state group and LHS observation. The containment failure mode comparison verifies the use of the EVNTRE and PSTEVNT codes, and their inputs. The risk potential comparison verifies the SEQSOR program. The risk comparison provides checks on the PARTITION and MACCS codes.

3.2 Containment Failure Mode Results

Table 1 presents the base case mean conditional probabilities of the accident progression bins (APBs) as calculated here (using the APETs) along with those reported by the Draft NUREG-1150 effort. As presented, these bins are consistent with the NUREG-1150 presentation (see Figure 2.5-3 of Reference 2), because the results are reported out to three decimal places. Probabilities less than 1.0E-03 are not reported. Also, two separate bins were reported in NUREG/CR-4551[2] as: no Vessel Breach (VB) with early CF, and no VB with no CF, have been combined into one bin, no VB with early or no CF. These two bins were not separately reported in NUREG-1150,[12] which was our primary reference before NUREG/CR-4551[2] became available.

The mean conditional probabilities for the summary APBs of a summary PDSG are obtained by weighting the conditional probabilities of the individual PDS by their mean core damage frequency for each set of PDS that constitute a particular summary group. Similarly, the total mean conditional APB probabilities are obtained by frequency weighting the summary PDS group results. The loss of offsite power (LOSP) PDSG consists of PDSs 1 and 2, the ATWS group of PDS 6, the transient group of PDS 5, the LOCA group of PDS 3, and the by-pass group of PDSs 4 and 7. The sum of the mean conditional probabilities over a summary PDS group will be slightly less than one because a truncation cutoff level of 1.0E-05 was used in the APET analysis. Sequences whose probability of occurrence was less than this cutoff frequency were dropped from the APET analysis.

Table 1. Sequoyah mean accident progression bin probabilities for PDS groups: comparison with NUREG/CR–4551 results

		PDS Group (mean core damage frequency)					
Accident Progression Bin	Case	LOSP (1.38E–05)	ATWS (2.07E–06)	Transients (2.32E–06)	LOCAs (3.52E–05)	Bypass (2.39E–06)	Total (5.58E–05)
CF[a] before VB,[b] early CF	Calculated:	0.014	0.003	< 1.0E–03	0.002	—	0.005
	NUREG/CR–4551:	0.014	0.003	—	0.002	—	0.005
VB, alpha, early CF	Calculated:	0.002	0.003	< 1.0E–03	0.002	—	0.002
	NUREG/CR–4551:	0.003	0.003	—	0.002	—	0.002
VB, RCS[c] > 200 psi, early CF	Calculated:	0.062	0.023	0.014	0.031	—	0.036
	NUREG/CR–4551:	0.064	0.023	0.014	0.031	—	0.035
VB, RCS < 200 psi, early CF	Calculated:	0.054	0.002	0.004	0.014	—	0.023
	NUREG/CR–4551:	0.054	0.002	0.004	0.014	—	0.023
VB, H_2 burn, late CF	Calculated:	0.149	0.001	< 1.0E–03	0.001	—	0.038
	NUREG/CR–4551:	0.153	0.001	—	0.001	—	0.038
VB, BMT[d] or very late OP[e]	Calculated:	0.066	0.151	0.039	0.260	—	0.187
	NUREG/CR–4551:	0.065	0.151	0.039	0.260	—	0.171
Bypass	Calculated:	0.001	0.134	0.006	—	0.996	0.048
	NUREG/CR–4551:	0.001	0.134	0.006	—	0.996	0.056
VB, no CF	Calculated:	0.204	0.471	0.137	0.301	—	0.263
	NUREG/CR–4551:	0.200	0.471	0.137	0.301	—	0.269

Table 1. (continued)

Accident Progression Bin	Case	PDS Group (mean core damage frequency) LOSP (1.38E–05)	ATWS (2.07E–06)	Transients (2.32E–06)	LOCAs (3.52E–05)	Bypass (2.39E–06)	Total (5.58E–05)
No VB, early or no CF	Calculated:	0.421	0.172	0.790	0.369	—	0.376
	NUREG/CR–4551:	0.422	0.172	0.790	0.369	—	0.382

a. Containment Failure.

b. Vessel Breach.

c. Reactor Coolant System.

d. Basemat Melt–through.

e. Overpressurization.

As seen from Table 1, the results calculated in this analysis compare quite well with those reported in NUREG/CR–4551. The close agreement of the results indicates that the base case accident progression analysis adequately duplicates that done in the NUREG/CR–4551 work.

3.3 Risk Results

Mean risk estimates were obtained using the methodology described in Section 2.1. The mean risk potentials in terms of early and latent fatality estimates obtained with PARTITION are compared in Table 2, with those reported in the SNL base case results.[a] The mean risk measures calculated using MACCS and those reported in NUREG/CR–4551, Vol. 5 are shown in Table 3. As seen in Table 2, the mean risk potentials calculated here match those reported by SNL. Again, this agreement of the results is an indication that our source term and partitioning analysis are equivalent to the original Sandia analysis. However, the mean risk measures, given in Table 3, do not compare as well, especially the estimate of mean early fatalities that deviate by 27% from the NUREG/CR–4551 estimate.

Some deviation in the mean risk measures was expected because the current analysis utilized an updated version of MACCS. This latest version (MACCS 1.5.11) includes some corrections to the version used in the Draft NUREG–1150 analyses (MACCS 1.5.5). However, the relatively large deviation in the mean early fatalities estimate as compared to the other risk measures was surprising. The cause of this deviation was further investigated by determining what the contributions to mean early fatalities are by sequence. It was determined that in the current analysis, 97.6% of the mean early fatality estimate (or 1.8E–05 early fatalities per reactor year) is attributable to the V–sequences of PDS 4. In the NUREG–1150 analyses, the V–sequence risk estimate is 1.8E–05 early fatalities per reactor year, but the fractional contribution is 68%. Clearly, the two analyses are in agreement for the mean early fatality risk results for the V–sequence. However, the current estimates for the balance of the sequences are much less than those calculated in the original NUREG–1150 analyses. The current analysis estimates the mean early fatalities per reactor year for all sequences, excluding

a. Information was taken from a report by J. J. Gregory entitled "Parametrics: NUREG–1150 Sensitivity Studies for the Sequoyah Plant," Draft Ice Condenser Parametrics Letter Report, December 1989.

Table 2. Sequoyah mean risk potentials: comparison to SNL base case results

	Mean Early Fatalities (per year)	Mean Latent Fatalities (per year)
Current analysis	8.3E–05	1.1E–01
SNL report	8.2E–05	1.1E–01

Table 3. Sequoyah base case mean risk measures: comparison to NUREG/CR–1150 base case results. Doses in person–rem per reactor year

	Mean Early Fatalities	Mean Latent Fatalities	Mean Dose 50–Mile	Mean Dose 1000–Mile
MACCS 1.5.11	1.9E–05	1.5E–02	1.1E+01	8.9E+01
NUREG/CR–4551	2.6E–05	1.4E–02	1.2E+01	8.1E+01
Percent difference	–27%	7%	–8%	10%

the V-sequences, at 4.6E-07, versus 8.3E-06 reported by Draft NUREG-1150. However, there is a discrepancy in the mean consequence results reported in Draft NUREG/CR-4551, Vol. 5 (specifically, Table 4.3-1 and Table C.1 of Reference 2). For example, for source term subgroups one and two, many of the early fatality results are one or two orders of magnitude smaller in Table 4.3-1 than in Table C.1. None of the early fatality results of Table 4.3-1 for these two subgroups are larger than those reported in Table C.1. Another interesting feature of these two tables is that the early fatality results for subgroup three are identical with two minor discrepancies. The early fatality results for source term groups SEQ-08-3 and SEQ-14-3 are reported as 1.62E+00 and 1.41E+02, and 1.61E+00 and 1.40E+02, in Tables 4.3-1 and C.1, respectively. Clearly, there are discrepancies in the results reported in Tables 4.3-1 and C.1 for source term subgroups one and two, but little or no difference for sub-group three. Coincidentally, our early fatality risk estimates for subgroups one and two are different than those reported in the NUREG/CR-4551, but are identical for subgroup three.

Presently, the reasons for these discrepancies in the mean early fatality risk measures and in the mean early fatality consequence measures reported in Draft NUREG/CR-4551, Vol. 5 are not clear. Therefore, the results calculated in this analysis will be referred to as the base case and will be used for comparative purposes in place of the NUREG-1150 results.

4. SCET DEVELOPMENT AND VERIFICATION

This section describes the construction of the SCETs. Also discussed is the verification of the SCET containment failure modes and risk results. The SCETs were developed for five of the seven plant damage states utilized in the NUREG–1150 analysis of Sequoyah.[2] The five plant damage state groups (PDSGs) analyzed here included short–term station blackout (SBO–ST), long–term station blackout (SBO–LT), loss–of–coolant accident (LOCA), transients, and Anticipated Transients Without Scram (ATWS). SCETs for the bypass PDSG, which included steam generator tube ruptures (SGTRs) and the event- V sequence, were not included because of their containment bypass nature.

The events modeled on each SCET are described in the section that follows along with a comparison of the SCETs containment failure mode (i.e., APB) probabilities with those calculated using the APETs. The two primary requirements in choosing the top events were to include all of the important containment failure modes and to provide sufficient detail to allow characterization of the source term release for each accident scenario (i.e., each SCET endstate). Because the SCETs are a condensed representation of the APETs, simplifications and approximations were utilized so that the most significant containment failure modes and source term characteristics were adequately represented while at the same time, producing a relatively simple model.

The construction of the SCETs is based on the methodology described in Chapter 2. Briefly, the EVNTRE accident progression analysis code[6] and the PSTEVNT[7] post processor code provided the essential tools for developing the SCETs from the APETs used in the NUREG–1150 analyses.

The structure of each SCET was developed utilizing the binning feature of the EVNTRE code. This feature allows the user to classify or bin each path through the APET in terms of selected APET question branches or combination of branches, which are of interest. The APET branches chosen for this purpose in turn define the SCET top events. This binner file that specifies the events of interest, is one of the input files used when running EVNTRE. The binner input decks used to create the SCETs are listed in Appendix C.

When evaluating the APETs, the sampling option of EVNTRE was used. As in the NUREG–1150 Sequoyah analysis, 200 samples or observations were specified for the EVNTRE runs used to create the SCETs. For each observation, the path taken through the APET is binned and saved in a post processing file. Using PSTEVNT, the resulting distribution of binned results was combined to form an aggregate or mean estimate of the 200 APET observations. PSTEVNT is again used to sort this mean estimate of the binned results to form the SCET branching structure as well as the branch conditional probabilities.

4.1 Top Event Selection for Each Plant Damage State Group

The selection of top events and the graphical SCET models are now presented. When reviewing the SCETs, the convention used here is that the events identified across the top of the tree (i.e., the failure events) are represented by a downward branching of the event tree. In this convention the downward branches describe the failure (or undesired) events and are associated with the event ID listed just below the event description. These failure events (and hence the down–branches) typically have low probabilities of occurrence. The upward branches are used for the successful or desired events that typically lead to an "ok" endstate. For sequences in which no branching occurs for a given event, the event does not occur (i.e., success) unless the branch is labeled with the event ID.

4.1.1 SBO–ST and SBO–LT SCET Top Event Descriptions. The SCETs for the short– and long–term station blackout plant damage states are shown in Figures 2 and 3, respectively.

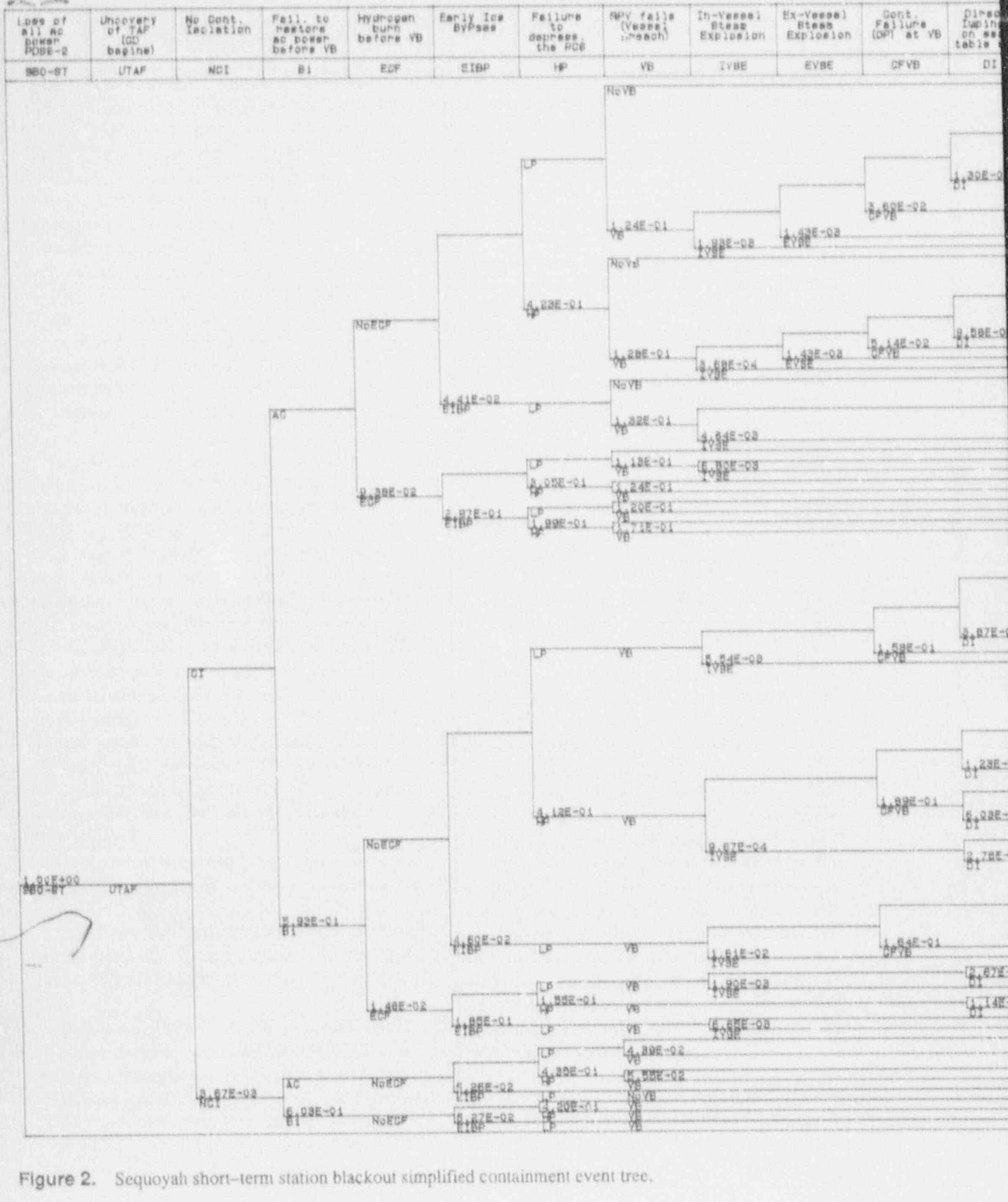
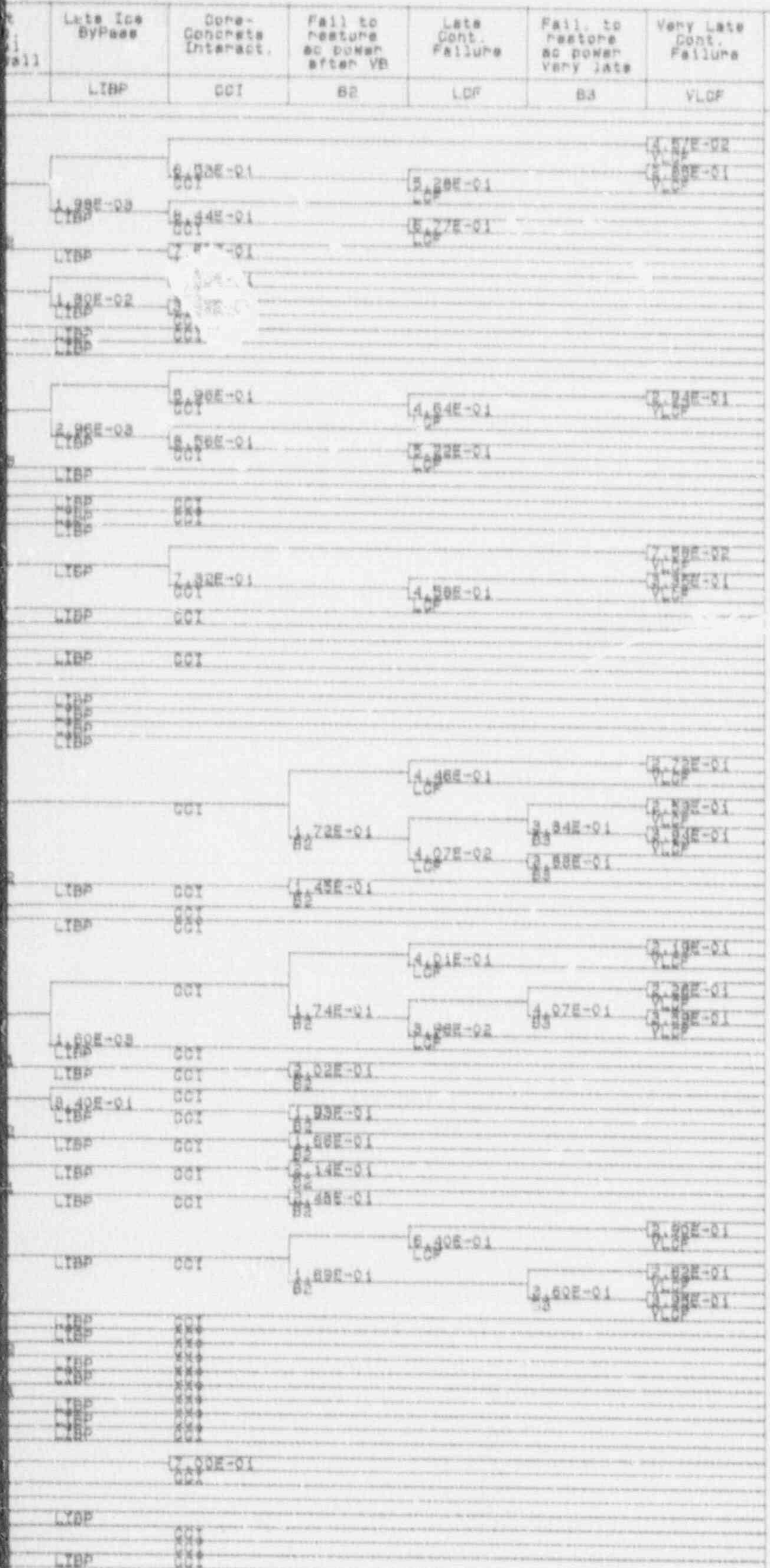


Figure 2. Sequoyah short–term station blackout simplified containment event tree.



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3.82E-04	SEQ-13-1	VLCF	3
5.81E-03	SEQ-12-1	VB-NCF	4
2.11E-03	SEQ-13-1	VLCF	5
8.31E-03	SEQ-13-1	LCF	6
7.43E-06	SEQ-12-1	VB-NCF	7
1.80E-05	SEQ-12-1	VB-NCF	8
2.73E-05	SEQ-14-1	LCF	9
7.33E-06	SEQ-14-2	ECF-LP	10
2.41E-05	SEQ-01-2	ECF-LP	11
3.91E-04	SEQ-01-2	ECF-LP	12
4.96E-04	SEQ-03-2	ECF-LP	13
9.79E-06	SEQ-01-2	ECF-LP	14
6.50E-06	SEQ-03-2	ECF-LP	15
8.59E-05	SEQ-01-2	ECF-LP	16
4.96E-05	SEQ-01-2	alpha	17
1.29E-01	SEQ-12-1	NoVB	18
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9.72E-04	SEQ-06-2	ECF-HP	27
2.70E-05	SEQ-05-2	ECF-HP	28
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1.08E-03	SEQ-10-2	CFbVB	43
1.86E-03	SEQ-08-2	NoVB	44
3.83E-04	SEQ-09-2	CFbVB	45
8.79E-02	SEQ-12-1	VB-NCF	46
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1.13E-03	SEQ-15-1	LCF	53
7.16E-04	SEQ-15-1	LCF	54
9.07E-03	SEQ-03-2	ECF-LP	55
1.54E-03	SEQ-05-2	ECF-LP	56
5.12E-02	SEQ-08-2	ECF-LP	57
1.81E-03	SEQ-08-2	alpha	58
6.28E-02	SEQ-12-1	VB-NCF	59
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8.38E-02	SEQ-13-1	LCF	61
1.25E-02	SEQ-12-1	VB-NCF	62
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1.11E-02	SEQ-06-2	ECF-HP	71
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2.17E-03	SEQ-06-2	ECF-HP	73
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1.26E-04	SEQ-05-2	alpha	75
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5.29E-04	SEQ-13-1	VLCF	85
4.33E-03	SEQ-10-2	ECF-LP	86
4.30E-04	SEQ-10-2	alpha	87
5.78E-03	SEQ-08-2	CFbVB	88
1.59E-04	SEQ-07-2	CFbVB	89
1.12E-05	SEQ-07-2	alpha	90
9.65E-04	SEQ-06-2	CFbVB	91
1.25E-04	SEQ-08-2	CFbVB	92
1.58E-03	SEQ-10-2	CFbVB	93
1.06E-05	SEQ-10-2	alpha	94
7.45E-04	SEQ-14-2	NoVB	95
1.03E-05	SEQ-15-2	CFbVB	96
2.39E-05	SEQ-01-2	CFbVB	97
5.86E-04	SEQ-14-2	NoVB	98
3.33E-05	SEQ-14-2	CFbVB	99
7.66E-05	SEQ-15-2	NoVB	100
1.22E-03	SEQ-08-2	CFbVB	101
8.81E-04	SEQ-05-2	CFbVB	102
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Sequoyah SCET — PDS8-2, 380-BT (fast) SQ-PD2.TRE 10/24/90

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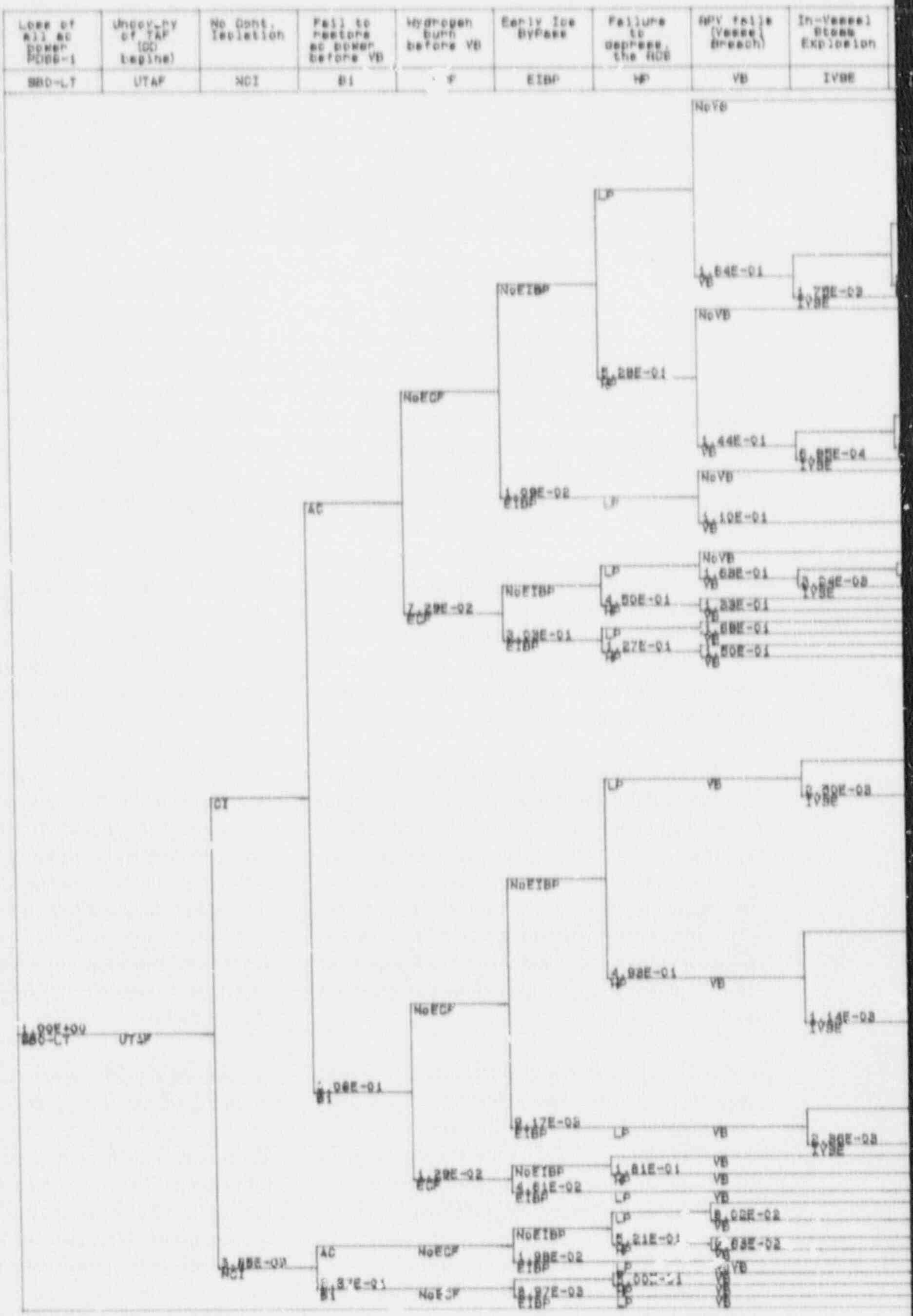
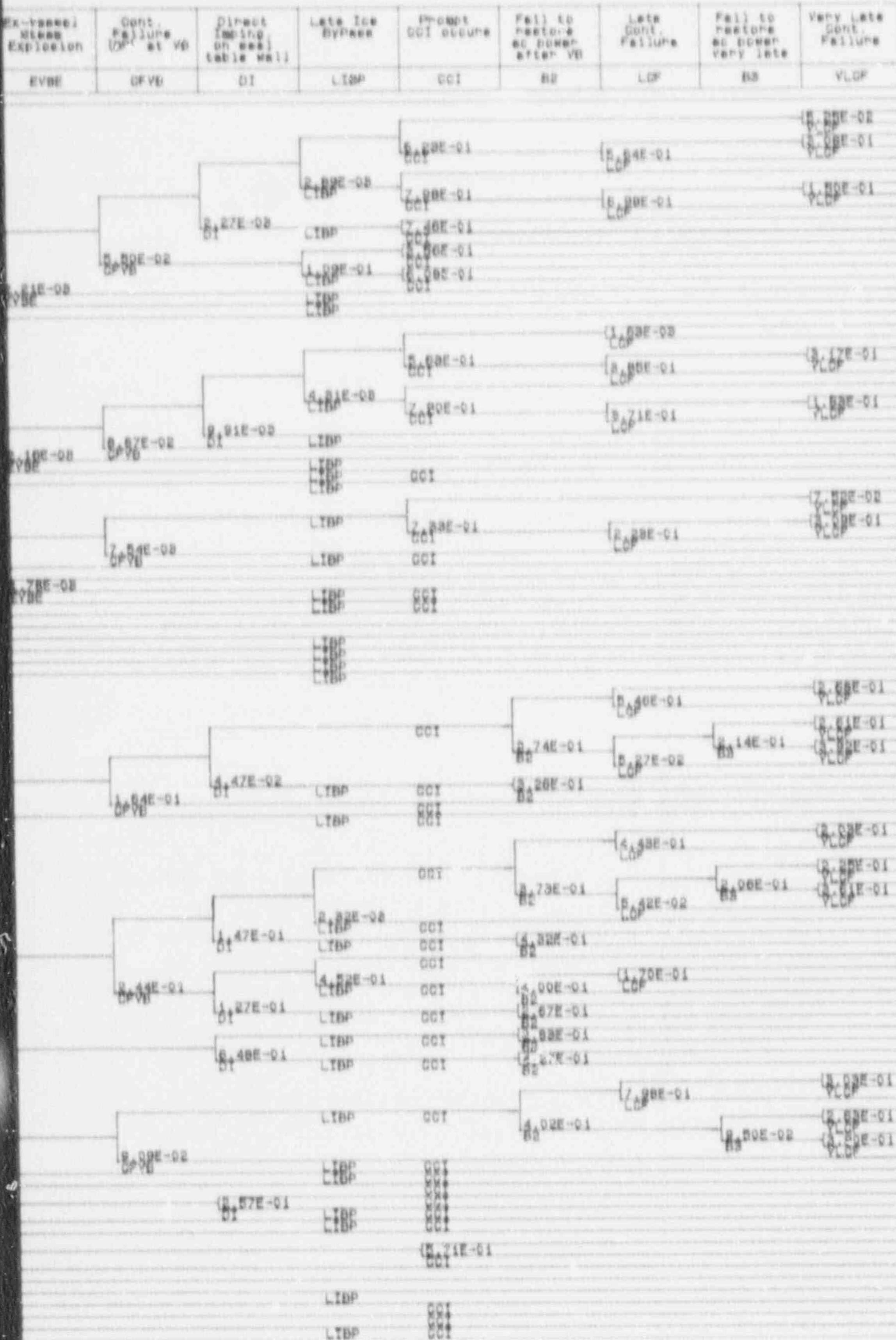


Figure 3. Sequoyah long-term station blackout simplified containment event tree.



SEQUENCE PROB.	SEQUENCE CLASS	CF Mode	ES No.
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7.63E-05	SEQ-01-2	ECF-LP	12
1.54E-03	SEQ-01-2	ECF-LP	13
8.52E-04	SEQ-03-2	ECF-LP	14
1.15E-04	SEQ-01-2	ECF-LP	15
1.78E-04	SEQ-03-2	ECF-LP	16
1.08E-04	SEQ-01-2	ECF-LP	17
8.57E-05	SEQ-01-2	alpha	18
2.86E-01	SEQ-12-1	NoVB	19
1.89E-02	SEQ-12-1	VB-NCF	20
3.08E-05	SEQ-13-1	LCF	21
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2.81E-05	SEQ-05-2	alpha	32
6.19E-03	SEQ-12-1	NoVB	33
1.88E-04	SEQ-12-1	VB-NCF	34
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3.00E-04	SEQ-12-1	VB-NCF	36
1.34E-04	SEQ-13-1	VLCF	37
1.25E-04	SEQ-14-1	LCF	38
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4.39E-03	SEQ-12-1	VB-NCF	67
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4.64E-05	SEQ-06-2	alpha	82
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4.38E-05	SEQ-15-2	CFbVB	97
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1.33E-04	SEQ-14-2	CFbVB	100
5.38E-05	SEQ-15-2	NoVB	101
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4.65E-04	SEQ-05-2	CFbVB	103
8.42E-06	SEQ-09-2	CFbVB	104

Sequoyah SGET -- PDS6-1, SBO-LT (slow) SQ-PD1.TRE 10/24/90

9101140284-02

The events for both station blackout trees are the same. However, the resulting branch structure and frequencies are different.

Loss of All ac Power. This first event identifies the PDS input to the SCET. For the SBO trees, the PDS is either the long– or short–term version of the sequence (SBO–LT or SBO–ST respectively).

The SBO–LT PDS is characterized by a loss of all ac power (both offsite grid connection and the onsite emergency diesel generators). However, dc power is initially available and consequently auxiliary feedwater (AFW), and instrumentation and control systems are initially available. When the batteries drain down (after approximately four hours), these systems are lost and core uncovery would begin about three hours later.

The SBO–ST PDS is also characterized by a loss of all ac power. For the short–term or fast SBO, either dc power or AFW is also lost initially. Therefore, as its name implies, it progresses to core uncovery much faster (i.e., a shorter term to core uncovery) than the SBO–LT sequence.

Uncovery of Top of Active Fuel (Core Damage Begins). By definition, entry into the SCET begins with the beginning of core uncovery. This is the moment that core damage is assumed to start and is used in the core damage frequency analysis[13] as the time at which recovery is impossible. Therefore, this event identifies the beginning of core damage for all sequences and is implicit in the accident progression analysis.

No Containment Isolation. This event questions if the containment leaks at a rate significantly larger than the design leak rate. If the containment is not isolated then the scenario is binned as an early containment failure mode. This issue is addressed by Question 12 of the APET.

Failure to Restore ac Power before Vessel Breach. This event questions if ac power has been restored between the time of core uncovery and vessel breach. Besides affecting the succeeding events in the accident progression, the source term release analysis utilizes this event in identifying whether the sprays and fans are operating. Note that, while failure to restore ac power early always results in vessel breach, containment failure can be still be averted. This top event is addressed by Question 22 of the APET.

Hydrogen Burn Before Vessel Breach. This event questions if the containment fails prior to or at vessel breach (i.e., early) because of a hydrogen detonation or deflagration. Question 58 of the APET was used to identify those APET scenarios that resulted in an early containment failure caused by hydrogen burns.

Early Ice Bypass. This top event questions whether a large bypass of the ice condenser occurs prior to vessel breach. The ice condenser is important for its pressure suppression capability and for removing fission products from the containment atmosphere. This event is used in the source term analysis to determine the decontamination factor up to the time of vessel breach. Question 59 of the APET addresses the status of the ice condenser before vessel breach and includes three options. Branch 1 identifies those sequences in which there is a large bypass of the ice condenser. Branch 2 identifies sequences in which the bypass of the ice condenser is minimal. The final branch identifies those sequences in which there is no early ice bypass and the ice condenser is totally effective. In creating the SCET, these latter two branches were combined to identify those sequences for which a large ice bypass did not occur.

Failure to Depressurize the RCS. This event questions whether the reactor coolant system has been depressurized before vessel breach, either intentionally or as a result of the accident progression. This event affects the potential for subsequent containment failure events such as the occurrence of DCH, in–vessel steam explosions, ex–vessel steam explosions, and type of core–concrete interaction (CCI). Therefore, this event is used in determining containment failure modes and in the source term analysis.

Question 25 of the APET was used in defining this event for the SCET. The APET question addresses what the vessel pressure is just before vessel breach and involves four branches identifying four vessel pressure levels. The four pressure levels are the system set point pressure–approximately 2500 psia; high pressure level—greater than 1000 psia but usually less than 2000 psia; the intermediate pressure level–about 200 to 600 psia; and the low pressure level–200 psia or less. Although, for the station blackout PDSs, all four pressure levels are possible, the majority of the sequences are at low pressure. In simplifying this event to a binary branch structure, depressurization of the RCS was identified as those sequences in which the sequences are at low pressure. All other sequences were regarded to involve failure to depressurize the reactor.

Reactor Pressure Vessel Fails (Vessel Breach). This top event questions whether or not the vessel fails. For those sequences in which the vessel fails, this event combined with other events (such as vessel pressure prior to breach), is used to identify the mode of vessel breach (and hence subsequent containment failure mechanisms) and to characterize the type of CCI.

Question 26 of the APET was to define this event for the SCET and determines whether or not core damage is arrested. The APET question has two options: no vessel breach and vessel breach. Because the APET question is binary, no simplification was necessary in creating the SCET event.

In–Vessel Steam Explosion. This event questions whether an in–vessel steam explosion (IVSE) fails the containment at vessel breach. An in–vessel steam explosion that fails the containment is commonly referred to as an alpha mode failure. Question 64 of the APET addresses this issue by asking: "if an IVSE occurs, does it fail the containment as well as the reactor pressure vessel (RPV)?" This APET question has two branches: alpha and no alpha. Again, because of this binary structure, no simplification was necessary in creating the SCET event.

Ex–Vessel Steam Explosion. This event questions if an ex–vessel steam explosion (EVSE) fails the containment at vessel breach. Question 71 of the APET addresses whether an EVSE at vessel breach occurs. There are three branches for this question. The first branch identifies those sequences in which an EVSE occurs but does not result in containment failure. The second branch identifies those sequences that involve an EVSE that does result in containment failure. The third branch identifies those sequences for which no EVSE occurs. In creating the SCET, the second branch was used to specify the sequences that involve an EVSE failing containment and the first and third branches were combined to identify those cases in which containment failure does not occur from an EVSE.

Containment Failure (Over–Pressurization) at Vessel Breach. This event questions if the containment fails from over–pressurization at vessel breach. Question 82 of the APET summarizes the containment failures at vessel breach, but includes both over–pressure failures and failures from steam explosions and rocket mode failures. (Although it is an insignificant contributor or containment failure probability, the rocket mode was included here for completeness.) Rocket mode failures occur when the vessel fails and is accelerated upward at high speed and fails the containment. Therefore, in creating the SCET event, the over-pressure failures were explicitly identified by binning those sequences that failed the containment as specified by Question 82, but did not involve an alpha, EVSE, or rocket mode of containment failure.

Direct Impingement on Seal Table Wall. This event questions if the containment fails by the direct contact of the molten core with the containment wall. Question 78 of the APET addresses this issue. The question contains two branches, the first affirmative and the second negative. Because of this binary structure, no simplification was necessary in creating the SCET top event.

Late Ice Bypass. This event questions whether a large bypass of the ice condenser occurs after vessel breach and is similar to the Early

Ice Bypass event discussed previously. The only difference in the two events is the timeframe in which they occur. This event is used in the source term binning to estimate the decontamination factor 5 to 30 minutes after vessel breach. Question 83 of the APET addresses the status of the ice condenser immediately after vessel breach and includes three possibilities. Branch 1 identifies those sequences in which there is a large ice bypass, and therefore the ice condenser is ineffective. Branch 2 identifies sequences in which the bypass of the ice condenser is minimal. The final branch identifies those sequences in which there is no ice bypass and the ice condenser is totally effective. In creating the SCET, these latter two branches were combined to identify those sequences for which a large ice bypass did not occur.

Prompt Core–Concrete Interaction Occurs. This event questions if prompt core concrete interaction occurs after vessel breach. This information is used to determine nature of the CCI for the source term analysis. Question 89 of the APET addresses the nature of a prompt CCI, but involves five branches. However, for the station blackout PDSs, only four of the branches are applicable. These four branches are described as follows: The first three branches all involve prompt CCI after vessel breach. The fourth branch is not applicable and the fifth branch involves those sequences for which prompt CCI does not occur. Of the three branches that involve prompt CCI, the first one occurs in a dry cavity, the second occurs with limited water from the reactor coolant system (RCS) inventory and the emergency core cooling system (ECCS) accumulators, and the third occurs in a wet or deeply flooded cavity (i.e. water depth is at least 10 ft) that would occur if the contents of the RWST were injected. In simplifying this branching structure for the SCET, the three prompt CCI branches were grouped together to characterize the prompt CCI event and the fourth and fifth branches were combined to form the no prompt CCI event. The nature of the prompt CCI for the source term estimation can be determined when this event is considered in combined with other events in the SCET.

Failure to Restore ac Power After Vessel Breach. This event questions if ac power is recovered late. Like the event that questions ac power before vessel breach, this event affects succeeding events in the accident progression and is used in identifying whether the sprays and fans are operating for the source term release analysis. Question 90 of the APET addresses the availability of ac power in the late timeframe. The question has three branches. The first branch identifies sequences in which power is available. The second and third branches involve sequences in which ac power is not available. For the second branch, ac power may be recovered in the future and cannot be recovered for the third branch. In simplifying this branch structure for the SCET, late ac power was identified with the first branch and failure to restore ac power late with the remaining branches.

Late Containment Failure. This event models the occurrence of containment failure caused by the pressure rise resulting from a late hydrogen deflagration. Question 103 of the APET summarizes the late containment failures and includes six branches. While the first branch identifies those APET scenarios that do not include a late containment failure, the remaining five branches identify the size of the failure and the area of containment in which the failure occurs. Therefore, in creating the SCET, the five containment failure branches were combined.

Failure To Restore ac Power Very Late. This event questions if ac power is restored in the very late timeframe. This event is used to determine if the sprays are operating during this time period. The status of the sprays is used in the source term estimation. Question 105 of the APET identifies if ac power is available in the very late timeframe. The question is binary with an affirmative and negative branch. Therefore, no simplification was required in creating the SCET event.

Very Late Containment Failure. This event questions whether the containment fails very late from overpressurization or basemat melt–through. In creating the SCET top event, the BMTs and very late overpressurizations were ssy oined using Question 107 and 109 of the APET, which address the BMT and very late containment failure events, respectively. Question 107 has two branches, and Question 109 has six. For Question 109, the first branch identifies those sequences for which the containment does not fail very late. The remaining branches all involve containment failures due to overpressurization. These various branches serve to characterize the failure size and location.

4.1.2 LOCA Top Event Descriptions. The SCET for the LOCA plant damage state is shown in Figure 4. Some of the events for the LOCA SCET are identical to those for the station blackout SCET and will not be repeated here.

LOCA. This first event identifies the PDS that defines the entry conditions for this particular SCET.

No Containment Isolation. This event is identical to the station blackout SCET event previously described.

Hydrogen Burn Before Vessel Breach. This event questions if the containment fails from a hydrogen detonation or deflagratic 1, before vessel breach. Question 58 of the APET addresses whether the containment fails prior to vessel breach and includes six branches. While the first branch identifies those APET scenarios that do not include an early containment failure, the remaining five branches identify the size and location of the containment failure. Therefore, for the SCET, early containment failure was determined by combining the five failure branches of Question 58. It should be noted that because of the availability of ac power (and therefore the hydrogen igniters), early containment failures are two orders of magnitude less likely for the LOCA PDS than for the station blackout PDSs.

Failure to Depressurize the RCS. This event is identical to the station blackout SCET event previously described.

Reactor Pressure Vessel Fails (Vessel Breach). This event is identical to the station blackout SCET event previously described.

Early Containment Heat Removal Unavailable. This event questions if the various modes of containment heat removal are available before VB. The heat removal systems include the containment sprays, the containment fans, and the ice condenser. This event affects succeeding events in the accident progression and is used to denote the operation of the containment sprays, a key parameter in estimating the source term. Questions 27, 28, 29, and 30 were utilized in creating this event for the SCET. Question 27 addresses the status of the early sprays; Question 28 examines the status of the air return fans; Question 29 ask if the ice has melted out of the ice condenser before vessel breach; and Question 30 inquires if the ice condenser has been bypassed prior to vessel breach.

In-Vessel Steam Explosion. This event is identical to that described for the station blackout PDSs except for the inclusion of the rocket mode of containment failure. Question 64 of the APET addresses the alpha mode event and Question 70 addresses the rocket mode failure event. Both questions are binary with Branch 1 identifying that the event occurs. These two APET questions were combined in creating the SCET event.

Ex-Vessel Steam Explosion. This event is identical to the station blackout SCET event previously described.

Containment Failure (Over-Pressurization) at Vessel Breach. This event questions if the containment fails due to over-pressurization at vessel breach. Question 82 of the APET summarizes the containment failures at vessel breach, but includes both over-pressure failures and failures attributable to steam explosions and failures prior to vessel breach. Therefore, in creating the SCET event, an overpressure failure was determined by identifying those sequences that failed the containment as specified by Question 82, but did not involve an alpha, EVSE, or earlier containment failure.

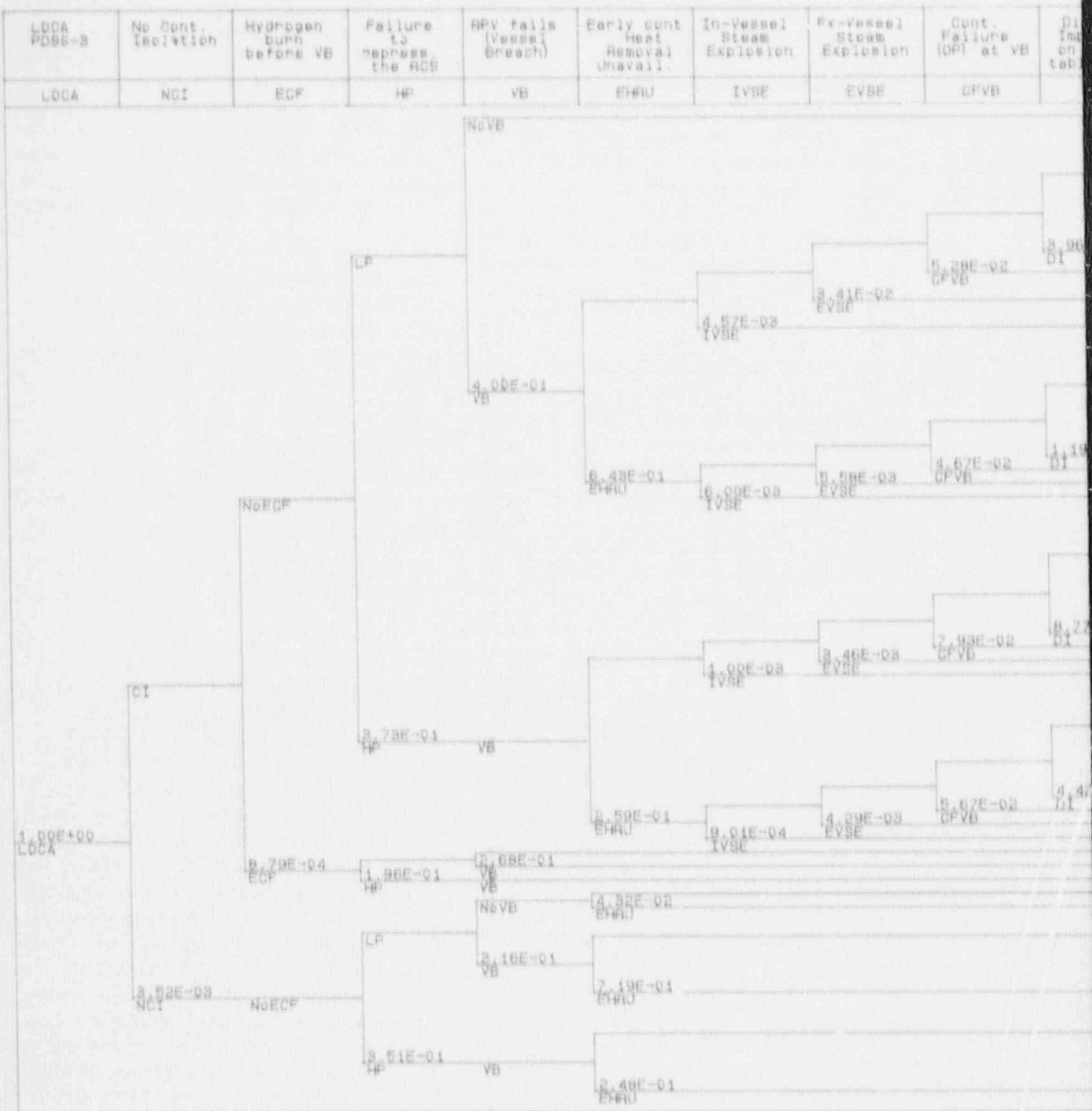
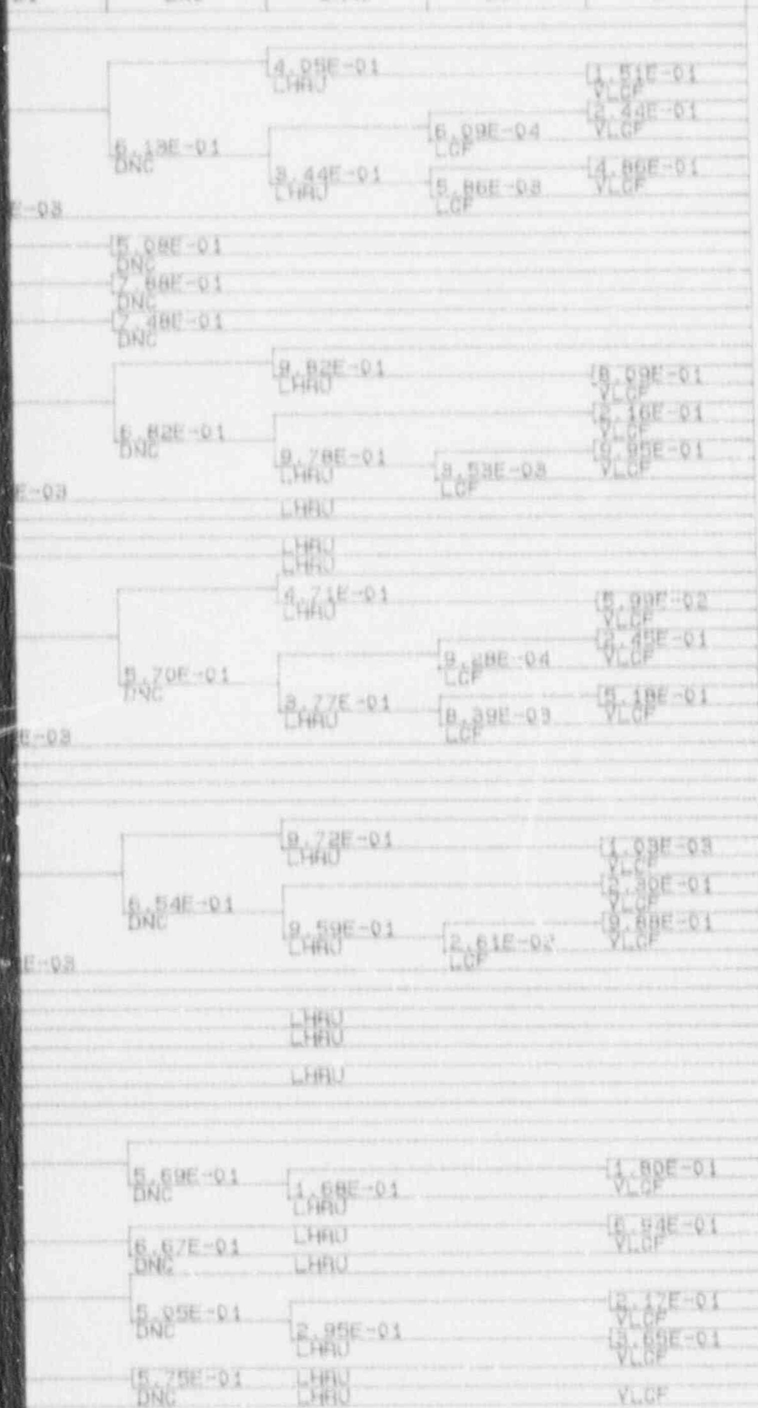


Figure 4. Sequoyah loss-of-coolant accident simplified containment event tree.

...rect ...ing. ...seal ...e wall	Debris bed is Not Coolable	Late cont Heat Removal Unavail.	Late Cont Failure	Very Late Cont. Failure
DI	DNC	LHRU	LCF	VLCF



SEQUENCE PROB.	SEQUENCE CLASS	CF Mode	ES No.
8.75E-01	SEQ-12-1	NoVB	1
1.82E-02	SEQ-12-1	VB-NCF	2
1.11E-02	SEQ-12-1	VB-NCF	3
1.97E-03	SEQ-13-1	VLCF	4
2.54E-02	SEQ-12-1	VB-NCF	5
8.19E-03	SEQ-13-1	VLCF	6
2.05E-05	SEQ-13-1	LCF	7
8.99E-03	SEQ-12-1	VB-NCF	8
8.50E-03	SEQ-13-1	VLCF	9
1.03E-04	SEQ-14-1	LCF	10
3.32E-04	SEQ-14-2	ECF-LP	11
2.30E-03	SEQ-01-2	ECF-LP	12
2.37E-03	SEQ-03-2	ECF-LP	13
6.42E-05	SEQ-01-2	ECF-LP	14
2.39E-04	SEQ-03-2	ECF-LP	15
1.03E-04	SEQ-01-2	alpha	16
3.05E-04	SEQ-03-2	alpha	17
8.84E-04	SEQ-12-1	VB-NCF	18
9.00E-03	SEQ-12-1	VB-NCF	19
3.81E-02	SEQ-13-1	VLCF	20
1.76E-03	SEQ-12-1	VB-NCF	21
4.85E-04	SEQ-13-1	VLCF	22
4.95E-04	SEQ-12-1	VB-NCF	23
9.99E-02	SEQ-13-1	VLCF	24
3.56E-04	SEQ-15-2	LCF	25
1.81E-04	SEQ-05-2	ECF-LP	26
7.40E-03	SEQ-09-2	ECF-LP	27
8.90E-04	SEQ-09-2	ECF-LP	28
9.63E-04	SEQ-09-2	alpha	29
5.69E-02	SEQ-12-1	VB-NCF	30
4.76E-02	SEQ-12-1	VB-NCF	31
3.03E-03	SEQ-13-1	VLCF	32
6.89E-02	SEQ-12-1	VB-NCF	33
2.17E-02	SEQ-13-1	VLCF	34
8.22E-05	SEQ-13-1	LCF	35
2.56E-02	SEQ-12-1	VB-NCF	36
2.76E-02	SEQ-13-1	VLCF	37
4.50E-04	SEQ-13-1	LCF	38
2.21E-02	SEQ-14-2	ECF-HP	39
2.17E-02	SEQ-06-2	ECF-HP	40
9.49E-04	SEQ-06-2	ECF-HP	41
2.76E-04	SEQ-06-2	alpha	42
8.70E-04	SEQ-12-1	VB-NCF	43
3.02E-02	SEQ-12-1	VB-NCF	44
3.11E-05	SEQ-13-1	VLCF	45
1.87E-03	SEQ-12-1	VB-NCF	46
5.59E-04	SEQ-13-1	VLCF	47
6.54E-04	SEQ-12-1	VB-NCF	48
5.55E-02	SEQ-13-1	VLCF	49
1.47E-04	SEQ-15-1	LCF	50
5.99E-04	SEQ-03-2	ECF-HP	51
5.42E-03	SEQ-08-2	ECF-HP	52
4.13E-04	SEQ-08-2	ECF-HP	53
8.67E-05	SEQ-08-2	alpha	54
5.15E-04	SEQ-06-2	NoVB	55
1.89E-04	SEQ-08-2	CFbVB	56
1.72E-04	SEQ-06-2	CFbVB	57
1.50E-03	SEQ-14-2	NoVB	58
6.75E-05	SEQ-06-2	NoVB	59
8.77E-05	SEQ-15-2	CFbVB	60
7.89E-05	SEQ-01-2	CFbVB	61
1.74E-05	SEQ-09-2	CFbVB	62
1.94E-05	SEQ-01-2	CFbVB	63
5.30E-05	SEQ-08-2	CFbVB	64
1.20E-04	SEQ-09-2	CFbVB	65
3.46E-04	SEQ-09-2	CFbVB	66
4.60E-04	SEQ-14-2	CFbVB	67
2.59E-04	SEQ-14-2	CFbVB	68
7.16E-05	SEQ-08-2	CFbVB	69
8.76E-05	SEQ-14-2	CFbVB	70
5.05E-05	SEQ-08-2	CFbVB	71
1.30E-04	SEQ-04-2	CFbVB	72
1.76E-04	SEQ-08-2	CFbVB	73

SCET -- PDS6-3, LOCA SQ-PD3.TRE 10/24/90

9101140284-03

Direct Impingement on Seal Table Wall. This event is identical to the station blackout SCET event previously described.

Debris Bed Is Not Coolable. This event models the probability of the debris bed forming a coolable configuration. This information is used to determine nature of the CCI for the source term analysis. Question 88 of the APET examines if the debris bed is in a coolable configuration and involves two branches. Because of this binary structure, no simplification was necessary in creating the SCET top event.

Late Containment Heat Removal Unavailable. This event questions if the various modes of containment heat removal have failed in the late or very late timeframes. The heat removal systems include the containment sprays and fans. This event affects succeeding events in the accident progression and is used in determining the operation of the sprays, which has an impact on the source term estimation. Questions 91, 92 and 106 were utilized in creating this event for the SCET. Question 91 addresses the status of the sprays late; Question 92 examines the status of the air return fans; and Question 106 addresses the status of sprays very late.

Late Containment Failure. This event is identical to the station blackout SCET event previously described.

Very Late Containment Failure. This event is identical to the station blackout SCET event previously described.

4.1.3 Transient Top Event Descriptions. The SCET for the transient PDSG is shown in Figure 5. Some of the events for the Transient SCET are identical to those for the station blackout and/or LOCA SCETs, and in such instances the descriptions will not be repeated here.

Transient. The transient plant damage state group is used to represent those sequences that cannot be categorized in one of the other seven PDSGs. That is, a transient sequence does not involve a loss of coolant (including SGTR and bypass sequences), a loss of all ac power, or a failure to trip the reactor, but does include a requirement for plant shutdown. The sequences comprised by this PDSG include situations where some of the systems required for safe shutdown have failed and core damage is imminent. This condition defines the entry condition for the transient SCET.

No Containment Isolation. This event is identical to the station blackout SCET event previously described.

Temperature Induced Steam Generator Tube Rupture. This event models the occurrence of a temperature induced steam generator tube rupture (SGTR), which is used in estimating the source term. Question 20 of the APET, which includes two branches, is used to define this event for the SCET. Because of its binary structure, no simplification was necessary.

Reactor Pressure Vessel Depressurized by RCS Failure. This event models the occurrence of a rupture in the RCS, which results in depressurizing the RPV before vessel breach. This event is used to identify if vessel failure occurs at high or low pressure.

Reactor Pressure Vessel Fails (Vessel Breach). This event is identical to the station blackout SCET event previously described.

Ex–Vessel Steam Explosion. This event is identical to the station blackout SCET event previously described.

Containment Failure (Over–Pressurization) at Vessel Breach. This event questions if the containment is failed from over–pressurization at vessel breach. Question 82 of the APET summarizes the containment failures at vessel breach, but includes both over–pressure failures and failures due to steam explosions and failures prior to vessel breach. Therefore, in creating the SCET event, an over-pressure failure was determined by identifying those sequences that failed the containment as specified by Question 82, but did not involve an EVSE induced failure or earlier containment failure.

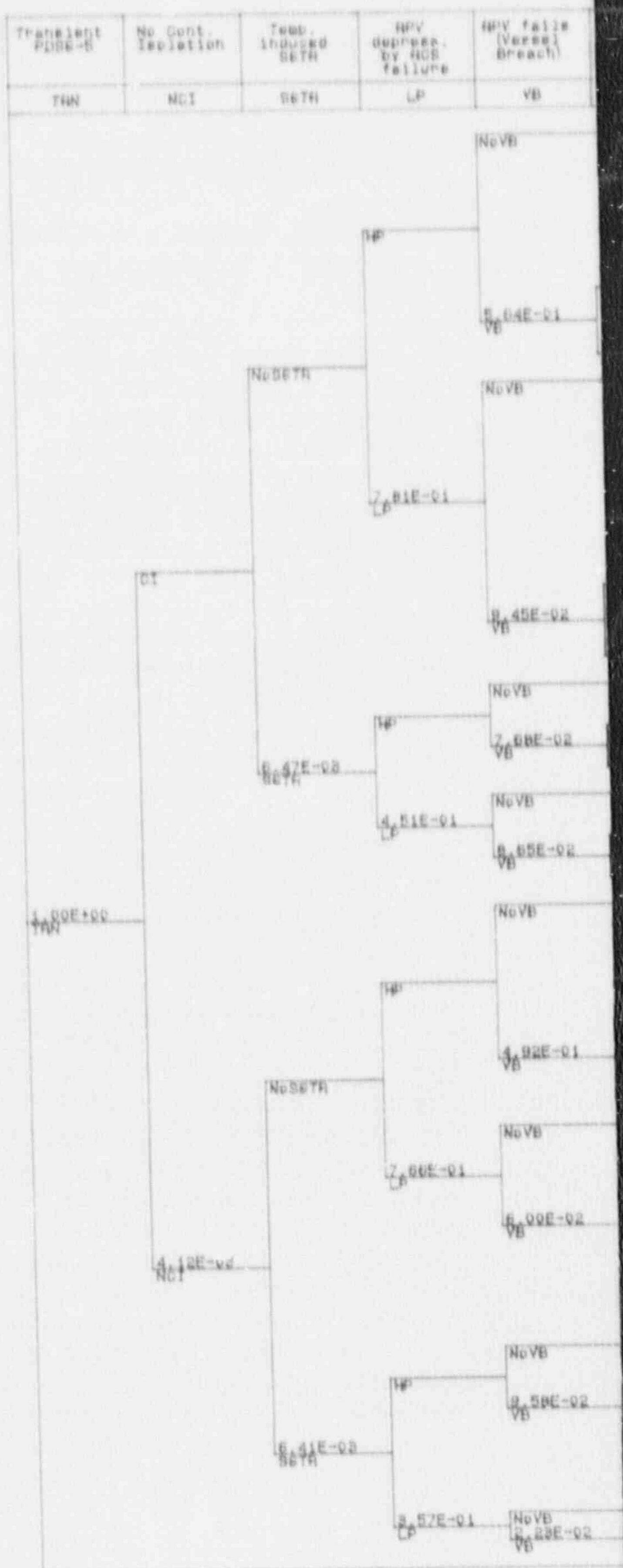
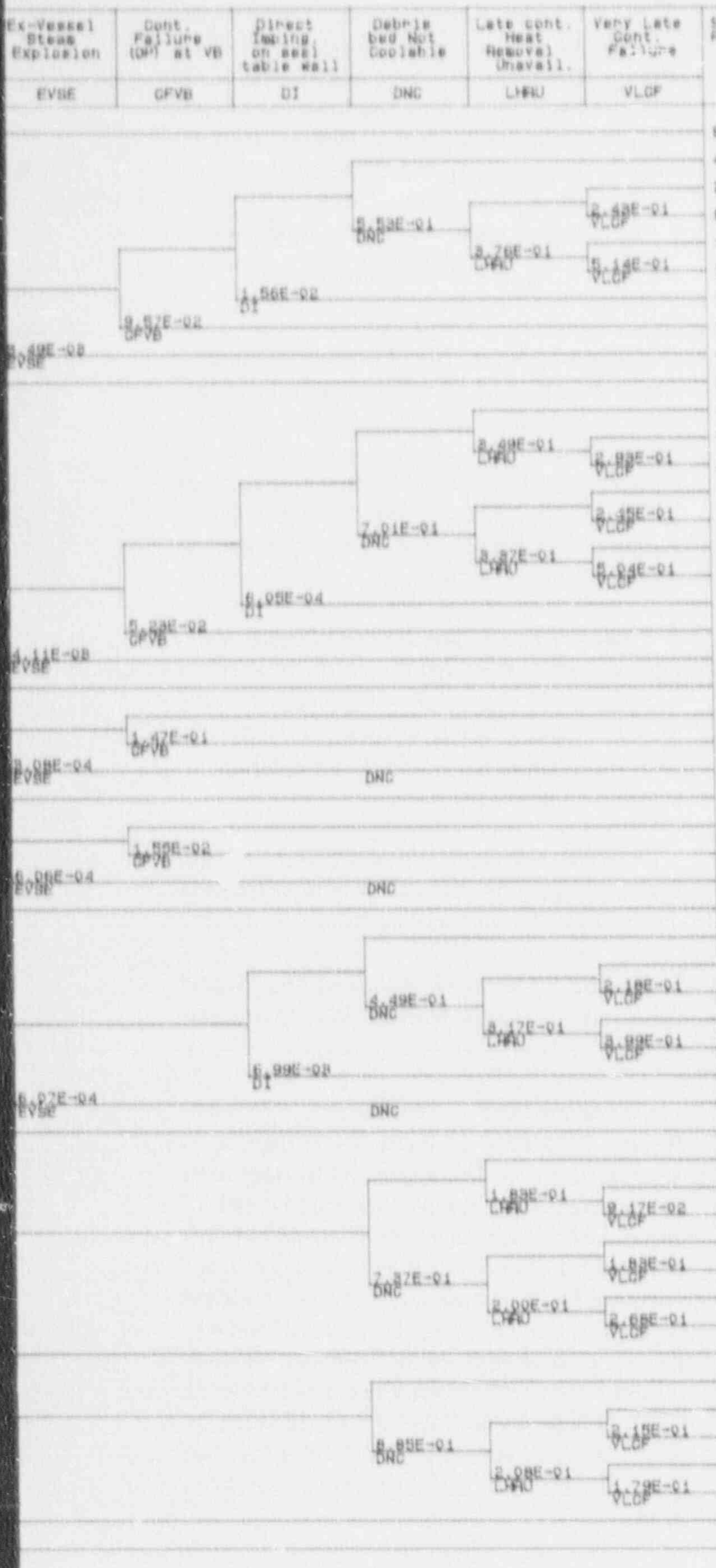


Figure 5. Sequoyah transient simplified containment event tree.



SEQUENCE PROB.	SEQUENCE CLASS	CF Mode	ES No.
9.43E-02	SEQ-12-1	NoVB	1
4.84E-02	SEQ-12-1	VB-NCF	2
2.83E-02	SEQ-12-1	VB-NCF	3
9.09E-03	SEQ-13-1	VLCF	4
1.10E-02	SEQ-12-1	VB-NCF	5
1.16E-02	SEQ-13-1	VLCF	6
1.71E-03	SEQ-14-2	ECF-HP	7
1.17E-02	SEQ-04-2	ECF-HP	8
4.27E-04	SEQ-04-2	ECF-HP	9
7.00E-01	SEQ-12-1	NoVB	10
1.84E-02	SEQ-12-1	VB-NCF	11
5.07E-03	SEQ-12-1	VB-NCF	12
2.10E-03	SEQ-13-1	VLCF	13
2.42E-02	SEQ-12-1	VB-NCF	14
7.86E-03	SEQ-13-1	VLCF	15
8.06E-03	SEQ-12-1	VB-NCF	16
8.21E-03	SEQ-13-1	VLCF	17
4.17E-05	SEQ-14-2	ECF-LP	18
3.80E-03	SEQ-03-2	ECF-LP	19
3.00E-04	SEQ-03-2	ECF-LP	20
3.27E-03	SEQ-07-2	bypass	21
7.32E-04	SEQ-07-2	bypass	22
3.99E-05	SEQ-09-2	bypass	23
6.37E-08	SEQ-09-2	bypass	24
2.66E-03	SEQ-07-2	bypass	25
2.48E-04	SEQ-07-2	bypass	26
3.90E-06	SEQ-07-2	bypass	27
1.52E-07	SEQ-09-2	bypass	28
4.86E-04	SEQ-14-2	NoVB	29
2.57E-04	SEQ-14-2	CFbVB	30
1.12E-04	SEQ-14-2	CFbVB	31
3.12E-05	SEQ-06-2	CFbVB	32
4.01E-05	SEQ-14-2	CFbVB	33
2.66E-05	SEQ-06-2	CFbVB	34
3.29E-06	SEQ-14-2	CFbVB	35
2.86E-07	SEQ-08-2	CFbVB	36
2.95E-03	SEQ-14-2	NoVB	37
4.04E-05	SEQ-15-2	CFbVB	38
8.24E-06	SEQ-15-2	CFbVB	39
8.32E-07	SEQ-09-2	CFbVB	40
9.06E-05	SEQ-01-2	CFbVB	41
2.04E-05	SEQ-09-2	CFbVB	42
2.04E-05	SEQ-01-2	CFbVB	43
7.47E-06	SEQ-09-2	CFbVB	44
1.54E-05	SEQ-07-2	bypass	45
1.87E-07	SEQ-07-2	bypass	46
8.97E-07	SEQ-07-2	bypass	47
2.46E-07	SEQ-09-2	bypass	48
2.46E-07	SEQ-07-2	bypass	49
5.36E-08	SEQ-09-2	bypass	50
9.21E-06	SEQ-07-2	bypass	51
2.11E-07	SEQ-07-2	bypass	52

Sequoyah SCET -- PDS6-5, Transient SQ-PD5.TRE 10/24/90

9101140284-04

Direct Impingement on Seal Table Wall. This event is identical to the station blackout SCET event previously described.

Debris Bed Is Not Coolable. This event is identical to the LOCA SCET event previously described.

Late Containment Heat Removal Unavailable. This event is identical to the LOCA SCET event previously described.

Very Late Containment Failure. This event is identical to the station blackout SCET event previously described.

4.1.4 ATWS Top Event Descriptions. The SCET for the ATWS plant damage state is shown in Figure 6. Some of the events for the ATWS SCET are identical to those for the station blackout and/or LOCA SCETs, in which case they will not be repeated here.

ATWS. The anticipated transients without scram (ATWS) PDSG represents those sequences that include a failure to shutdown the reactor. Again, this first event identifies the entry condition for the ATWS SCET, which implies imminent core damage.

Steam Generator Tube Rupture Initially Present. This event segregated those scenarios in which SGTR is initially present. For the ATWS PDS, the size and location of the RCS break at the time of core uncovery can be either a very small break in the RCS piping, coolant loss through the cycling PORVs or SRVs, or a SGTR. Question 1, Branch 5 of the APET identifies the SGTR initiating event. The SGTR event is a key parameter in the source term estimate (i.e., containment bypass).

No Containment Isolation. This event is identical to the station blackout SCET event previously described.

Hydrogen Burn Before Vessel Breach. This event is identical to the LOCA SCET event previously described.

Failure to Depressurize the RCS. This event is identical to the station blackout SCET event previously described.

Reactor Pressure Vessel Fails (Vessel Breach). This event is identical to the station blackout SCET event previously described.

In-Vessel Steam Explosion. This event is identical to the LOCA SCET event previously described.

Ex-Vessel Steam Explosion. This event is identical to the station blackout SCET event previously described.

Containment Failure (Over-Pressurization) at Vessel Breach. This event is identical to the LOCA SCET event previously described.

Direct Impingement on Seal Table Wall. This event is identical to the station blackout SCET event previously described.

Debris Bed Is Not Coolable. This event is identical to the LOCA SCET event previously described.

Late Containment Heat Removal Unavailable. This event is identical to the LOCA SCET event previously described.

Late Containment Failure. This event is identical to the station blackout SCET event previously described.

Very Late Containment Failure. This event is identical to the station blackout SCET event previously described.

4.2 Containment Failure Modes

In order to support the use of the SCETs in estimating risk and for evaluating the benefits of potential containment improvements, the containment failure mode probabilities were calculated and compared with the base case APET results.

4.2.1 Containment Failure Mode Binning. After loading the SCETs into the ETA-II event

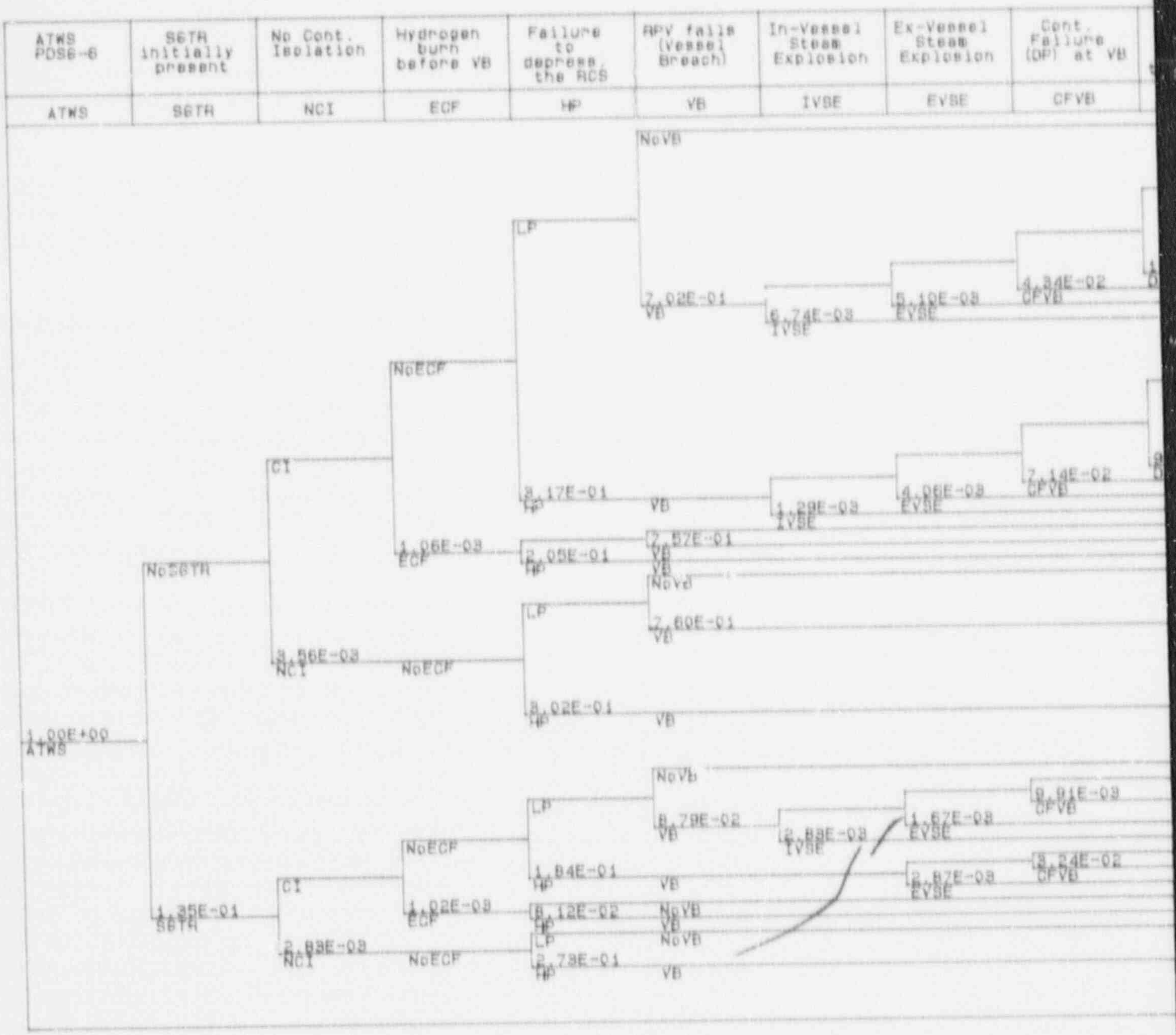
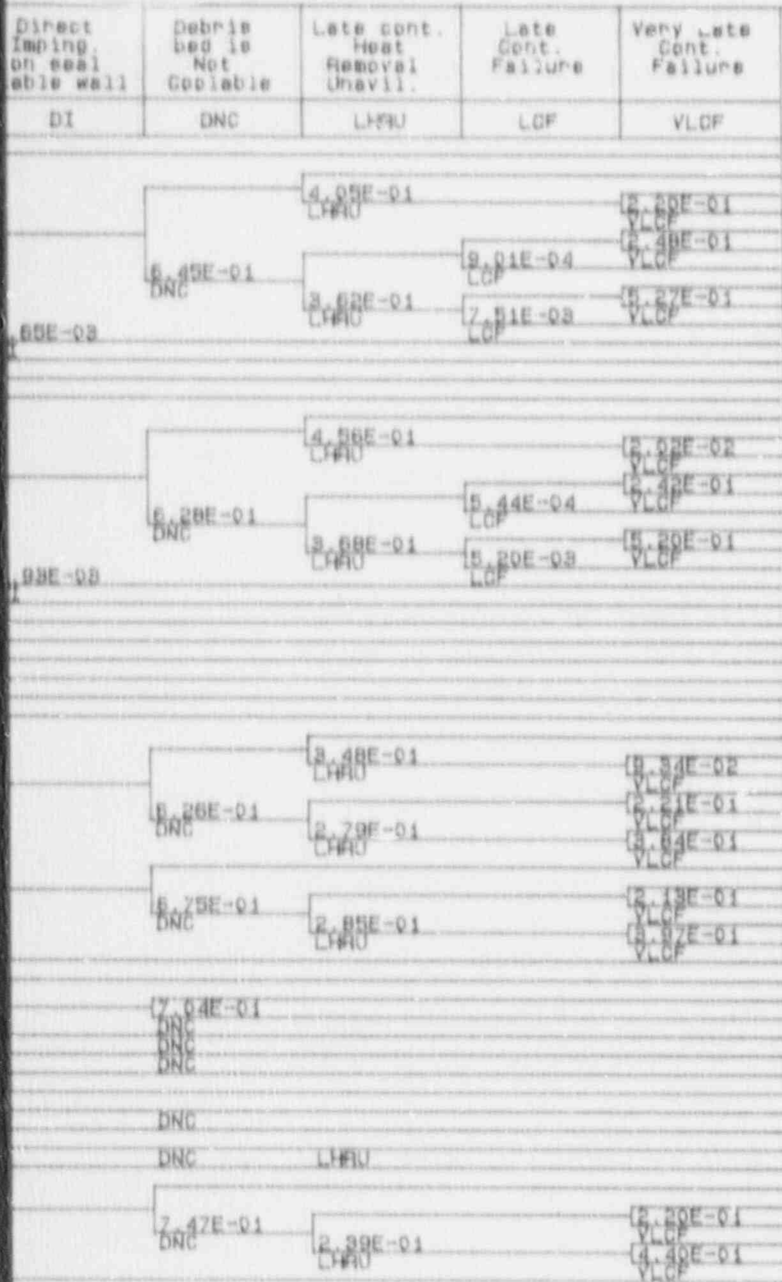


Figure 6. Sequoyah anticipated transient without scram simplified containment event tree.



SEQUENCE PROB.	SEQUENCE CLASS	CF Mods	ES No.
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8.22E-02	SEQ-12-1	VB-NCF	2
4.36E-02	SEQ-12-1	VB-NCF	3
1.23E-02	SEQ-13-1	VLCF	4
1.20E-01	SEQ-12-1	VB-NCF	5
3.98E-02	SEQ-13-1	VLCF	6
1.44E-04	SEQ-13-1	LCF	7
4.26E-02	SEQ-12-1	VB-NCF	8
4.75E-02	SEQ-13-1	VLCF	9
6.82E-04	SEQ-14-1	LCF	10
6.44E-04	SEQ-14-2	ECF-LP	11
1.77E-02	SEQ-03-2	ECF-LP	12
2.09E-03	SEQ-01-2	ECF-LP	13
2.78E-03	SEQ-01-2	alpha	14
5.05E-02	SEQ-12-1	VB-NCF	15
4.15E-02	SEQ-12-1	VB-NCF	16
8.57E-04	SEQ-13-1	VLCF	17
7.49E-02	SEQ-12-1	VB-NCF	18
2.40E-02	SEQ-13-1	VLCF	19
5.38E-05	SEQ-13-1	LCF	20
2.73E-02	SEQ-12-1	VB-NCF	21
2.98E-02	SEQ-13-1	VLCF	22
3.00E-04	SEQ-13-1	LCF	23
2.50E-03	SEQ-14-2	ECF-HP	24
1.54E-02	SEQ-06-2	ECF-HP	25
1.11E-03	SEQ-05-2	ECF-HP	26
3.51E-04	SEQ-05-2	alpha	27
1.77E-04	SEQ-08-2	NoVB	28
5.52E-04	SEQ-09-2	CFbVB	29
1.88E-04	SEQ-08-2	CFbVB	30
5.15E-04	SEQ-14-2	NoVB	31
3.97E-04	SEQ-15-2	CFbVB	32
1.92E-04	SEQ-15-2	CFbVB	33
1.98E-05	SEQ-09-2	CFbVB	34
5.74E-04	SEQ-01-2	CFbVB	35
1.63E-04	SEQ-09-2	CFbVB	36
1.75E-04	SEQ-01-2	CFbVB	37
1.09E-04	SEQ-09-2	CFbVB	38
3.03E-04	SEQ-14-2	CFbVB	39
3.53E-04	SEQ-14-2	CFbVB	40
9.56E-05	SEQ-08-2	CFbVB	41
1.08E-04	SEQ-14-2	CFbVB	42
7.10E-05	SEQ-08-2	CFbVB	43
1.00E-01	SEQ-07-2	bypass	44
9.51E-03	SEQ-07-2	bypass	45
2.82E-05	SEQ-07-2	bypass	46
6.71E-05	SEQ-09-2	bypass	47
1.61E-05	SEQ-09-2	bypass	48
2.74E-05	SEQ-09-2	bypass	49
2.38E-02	SEQ-07-2	bypass	50
7.98E-04	SEQ-09-2	bypass	51
7.08E-05	SEQ-09-2	bypass	52
1.27E-04	SEQ-09-2	bypass	53
1.12E-05	SEQ-09-2	bypass	54
2.78E-04	SEQ-07-2	bypass	55
2.64E-05	SEQ-07-2	bypass	56
4.32E-05	SEQ-07-2	bypass	57
1.22E-05	SEQ-09-2	bypass	58
1.26E-05	SEQ-07-2	bypass	59
9.90E-06	SEQ-09-2	bypass	60

SCET -- PDS6-6, ATWS SQ-PD6.TRE 10/25/90

9101140284-05

tree software package, the event tree endstates were binned according to containment failure mode. In binning the endstates, the NUREG–1150 presentation bins were used. For Sequoyah, there are ten bins. The ten accident progression summary bins are:

- VB, very early (during CD) CF or isolation failures
- VB, early (at VB) CF or alpha mode
- VB with the RCS pressure > 200 psia, early (at VB) CF
- VB with the RCS pressure < 200 psia, early (at VB) CF
- VB, late CF
- VB, BMT or very late CF
- Bypass
- VB, no CF
- No VB, but with very early (during CD) CF or isolation failures
- No VB, no CF.

In presenting the results, the last two bins were combined into a single bin and renamed No Vessel Breach. For the actual process of assigning each endstate to one of these summary bins, the bins were considered in a hierarchical order as follows:

- Bypass
- VB, early (at VB) CF or alpha mode
- No VB
- VB, very early (during CD) CF or isolation failures
- VB with RCS pressure > 200 psia, early (at VB) CF (at VB)
- VB with RCS pressure < 200 psia, early (at VB) CF (at VB)
- VB, late CF
- VB, BMT or very late CF
- VB, no CF.

This ordering of the summary bins was required because some endstates satisfy the criteria for more than one containment failure mode. For these cases, the sequence is placed into the most appropriate (with respect to source term definition) bin.

4.2.2 Containment Failure Mode Comparison With APET Results. For each SCET, the containment failure mode results are presented and compared with the results of the APET analysis presented in Chapter 3.

SBO–LT Containment Failure Mode Results. Table 4 compares the accident progression summary bin probabilities for the SBO–LT PDS, as predicted by the SCET and the APET. The SBO–LT SCET results compare quite well with the full APET results. The one exception is the bypass bin. For the SCET, the probability of bypass is zero because this event was not included in the simplified tree. For the SBO PDSs, the bypass bin includes only those scenarios involving a temperature–induced SGTR. This event was not included in the SCET because of the low probability of occurrence as estimated by the APET. Overall, these results indicate that the SCET accurately models the containment failure modes for the SBO–LT PDS. As a final note, the sum of the bin probabilities do not necessarily add to unity because of rounding off error for the SCET results and because of truncation in the APET results.

SBO–ST Containment Failure Mode Results. Table 5 compares the accident progression summary bin probabilities for the SBO–LT PDS, as predicted by the SCET and the APET. The SBO–LT SCET results compare quite well with the full APET results. As is the case for the SBO–ST PDS, the one exception for the SBO–ST, is the bypass bin. Again, this event was not included in the SCET because of the low probability of occurrence as predicted by the APET.

LOCA Containment Failure Mode Results. Table 6 compares the accident progression summary bin probabilities for the LOCA PDS, as predicted by the SCET and the APET. The LOCA SCET results compare quite well with the full APET results.

Table 4. Comparison of SCET and APET accident progression bin mean probabilities for SBO–LT PDS at Sequoyah

Accident Progression Bin	SCET	APET
CF[a] before VB,[b] early CF (CFbVB)	1.2E–02	1.2E–02
VB, alpha, early CF (alpha)	6.6E–04	6.9E–04
VB, RCS[c] > 200 psi, early CF (ECF–HP)	4.2E–02	5.5E–02
VB, RCS < 200 psi, early CF (ECF–LP)	3.3E–02	3.2E–02
VB, late CF (LCF)	9.7E–02	9.6E–02
VB, BMT[d] or very late OP[e] (VLCF)	4.5E–02	4.5E–02
Bypass	0.0	1.3E–04
VB, no CF (VB–NCF)	1.7E–01	1.6E–01
No VB, early or no CF (NoVB)	5.7E–01	5.7E–01

a. Containment failure.

b. Vessel Breach.

c. Reactor coolant system.

d. Basemat melt–through.

e. Overpressurization.

Table 5. Comparison of SCET and APET accident progression bin mean probabilities for SBO–ST PDS at Sequoyah

Accident Progression Bin	SCET	APET
CF[a] before VB,[b] early CF (CFbVB)	1.5E–02	1.5E–02
VB, alpha, early CF (alpha)	2.5E–03	2.5E–03
VB, RCS[c] > 200 psi, early CF (ECF–HP)	6.6E–02	6.6E–02
VB, RCS < 200 psi, early CF (ECF–LP)	6.5E–02	6.5E–02
VB, late CF (LCF)	1.8E–01	1.8E–01
VB, BMT[d] or very late OP[e] (VLCF)	7.7E–02	7.7E–02
Bypass	0.0	1.7E–03
VB, no CF (VB–NCF)	2.3E–01	2.3E–01
No VB, early or no CF (NoVB)	3.5E–01	3.5E–01

a. Containment failure.

b. Vessel Breach.

c. Reactor Coolant System.

d. Basemat melt–through.

e. Overpressurization.

Table 6. Comparison of SCET and APET accident progression bin mean probabilities for LOCA PDS at Sequoyah

Accident Progression Bin	SCET	APET
CF[a] before VB,[b] early CF (CFbVB)	2.3E–03	2.3E–03
VB, alpha, early CF (alpha)	1.7E–03	1.7E–03
VB, RCS[c] > 200 psi, early CF (ECF–HP)	3.0E–02	3.0E–02
VB, RCS < 200 psi, early CF (ECF–LP)	1.3E–02	1.3E–02
VB, late CF (LCF)	1.1E–03	1.1E–03
VB, BMT[d] or very late OP[e] (VLCF)	2.6E–01	2.6E–01
Bypass	—	—
VB, no CF (VB–NCF)	3.0E–01	3.0E–01
No VB, early or no CF (NoVB)	3.7E–01	3.7E–01

a. Containment failure.

b. Vessel Breach.

c. Reactor coolant system.

d. Basemat melt–through.

e. Overpressurization.

Transient Containment Failure Mode Results. Table 7 compares the accident progression summary bin probabilities for the Transient PDS, as predicted by the SCET and the APET. The Transient SCET results compare quite well with the full APET results. Two exceptions are the alpha and late CF bins. For the SCET, the probability of these two bins is zero. These events were not included in the SCET because of their low probability of occurrence as estimated by the APET. Overall, these results indicate that the SCET accurately models the containment failure modes for the Transient PDS.

ATWS Containment Failure Mode Results. Table 8 compares the accident progression summary bin probabilities for the ATWS PDS, as predicted by the SCET and the APET. The ATWS SCET results compare quite well with the full APET results.

Table 7. Comparison of SCET and APET accident progression bin mean probabilities for Transient PDS at Sequoyah

Accident Progression Bin	SCET	APET
CF[a] before VB,[b] early CF (CFbVB)	6.5E–04	7.3E–04
VB, alpha, early CF (alpha)	0.0	3.9E–04
VB, RCS[c] > 200 psi, early CF (ECF–HP)	1.4E–02	1.4E–02
VB, RCS < 200 psi, early CF (ECF–LP)	4.1E–03	3.8E–03
VB, late CF (LCF)	0.0	8.2E–05
VB, BMT[d] or very late OP[e] (VLCF)	3.8E–02	3.8E–02
Bypass	6.4E–03	6.4E–03
VB, no CF (VB–NCF)	1.4E–01	1.4E–01
No VB, early or no CF (NoVB)	7.9E–01	7.9E–01

a. Containment failure.

b. Vessel Breach.

c. Reactor Coolant System.

d. Basemat melt–through.

e. Overpressurization.

Table 8. Comparison of SCET and APET accident progression bin mean probabilities for ATWS PDS at Sequoyah

Accident Progression Bin	SCET	APET
CF[a] before VB,[b] early CF (CFbVB)	3.2E–03	3.2E–03
VB, alpha, early CF (alpha)	3.1E–03	3.1E–03
VB, RCS[c] > 200 psi, early CF (ECF–HP)	2.2E–02	2.3E–02
VB, RCS < 200 psi, early CF (ECF–LP)	2.0E–02	2.0E–02
VB, late CF (LCF)	1.1E–03	1.1E–03
VB, BMT[d] or very late OP[e] (VLCF)	1.5E–01	1.5E–01
Bypass	1.3E–01	1.3E–01
VB, no CF (VB–NCF)	4.7E–01	4.7E–01
No VB, early or no CF (NoVB)	1.7E–01	1.7E–01

a. Containment failure.

b. Vessel Breach.

c. Reactor Coolant System.

d. Basemat melt–through.

e. Overpressurization.

4.3 Risk

Risk is calculated by assembling the results from the plant damage frequency (level–1) analysis, the containment failure (level–2) analysis, and the offsite consequence (level–3) analysis. The equation representing the assembly of these three parts of a complete risk analysis can be expressed as follows:

$$RISK_k = \sum_i \sum_j FREQ_i * CRMP_{ij} * CONS_k(FP_{ij}) \qquad (1)$$

where

$RISK_k$ = the risk associated with consequence measure k

$FREQ_i$ = the frequency of plant damage state group i

$CRMP_{ij}$ = the conditional probability of containment release mode j, given plant damage state group i

FP_{ij} = fission product source term for containment release mode j of plant damage state group i

CONS$_k$ = mean magnitude of consequence k, given fission product source term (FP_{ij}).

The frequency of each plant damage state group is obtained from the Sequoyah level–1 PRA.[13] The containment failure mode probabilities are obtained from the SCETs presented in Section 4.1 and the binning procedure described in Section 4.2.1. The consequence data are obtained by determining a source term for each release mode and then calculating a consequence for each source term. This is a two–step process and is described below in Sections 4.3.2 and 4.3.3.

4.3.1 Release Mode Probabilities. A conditional probability for each containment release mode is obtained by rebinning the endstates of the SCETs described in Section 4.1, into source term release groups or bins. The rebinning relies on the framework established in the NUREG–1150 analysis of Sequoyah.[2] Each SCET endstate is assigned a source term vector that comprises fourteen characteristics. These characteristics, which are defined in Table 9, are then used to define the source term resulting from a particular path through the event tree.

Each of the above characteristics and its possible values, are defined in Section 2.4.2 of Reference 2. As an aid to understanding the following discussions, commented listings of the PSTEVNT binning data files are provided in Appendix C. These listings provide a detailed record of how the source term bins were created for this analysis. However, the data files are difficult to interpret without some familiarity with PSTEVNT. Therefore, the following example is provided:

Table 9. Source term characteristic definitions

Characteristic	Mnemonic	Description
1	CF–Time	Time of containment failure
2	Sprays	Periods in which sprays operate
3	CCI	Occurrence of core–concrete interactions
4	RCS–Pres	RCS pressure before vessel breach
5	VB–Mode	Mode of vessel breach
6	SGTR	Steam generator tube rupture
7	AMT–CCI	Amount of core available for CCI
8	Zr–Ox	Fraction of Zr oxidized in–vessel
9	HPME	Fraction of core in HPME
10	CF–Size	Size of containment failure
11	RCS–Hole	Number of large holes in the RCS after VB
12	E2–IC	Early ice condenser function
13	I2–IC	Late ice condenser function
14	ARFans	Status of air return fans

```
        Sequoyah Source Term Rebinning -- PDSG-1 and 2, SBO
14      CF-Time          Sprays       CCI          RCS-Pres     VB-Mode     SGTR
        Amt-CCI          Zr-Ox        HPME         CF-Size      RCS-Hole    E2-IC
         I2-IC           ARFans
7  7    V-Dry            V-Wet        CF-Early     CF-atVB      CF-Late     CF-VLate
        NoCF
2  1       1     1                    $ A.         Event V, not scrubbed
           1*    /1
        V-Dry
2  2       1     1                    $ B.         Event V, scrubbed
           1*    /1
        V-Wet
2  3       1     3                    $ C.         CF during core degradation
           2+    2
        CF-Early
4  4       7  8  9  10                $ D.         CF at vessel breach
           2 + 2 + 2 + 2
        CF-atVB
1  5       14                         $ E.         Late CF
            2
        CF-Late
1  6       16                         $ F.         Very late CF
            2
        CF-VLate
8  7     1  3  7  8  9  10  14  16    $ G.         No containment failure
         1 * 1 * 1 * 1 * 1 * 1 * 1 * 1
         NoCF
```

Those familiar with EVNTRE and PSTEVNT input will recognize that a portion of this data fragment (specifically, lines 2, 3, and 4) identifies the 14 characteristics of the source term vector listed in Table 9. The balance of the data fragment then defines the rules for determining the first characteristic of the vector; in this case, time of containment failure. There are seven options this characteristic can assume, they are (abbreviated): V-Dry, V-Wet, CF-Early, etc. The selection logic for each attribute follows. For example, the logic statements indicate option A (representing V-Dry) cannot occur for this PDSG. The comment (indicated by the "$" character) explains that attribute A is assigned only for V sequences with a dry release (i.e., not scrubbed). The numbers used in the logic statements refer to the SCET top event number and branch number. For a complete description of the EVNTRE and PSTEVNT data requirements, the reader should refer to References 6 and 7 (EVNTRE and PSTEVNT manuals). The following discussions explain the application of the NUREG-1150 binning scheme to the SCETs.

Containment Failure Time. *The time at which containment fails* is described in terms of seven attributes or options. The first two characterize the nature of V-events, and therefore never appear in SCET source term binning results. The remaining options define the time of containment failure as occurring during core degradation, at vessel breach, late, very late, or never.

During SBO, LOCA, and ATWS sequences, early containment failures (i.e., during core degradation) are composed almost entirely of failure to isolate, and hydrogen burn events. Both of these appear on the SBO, LOCA, and ATWS SCETs and are used by the binner to identify scenarios that include early containment failures. The transient SCET does not include a hydrogen-burn-caused containment failure event during core degradation because of its relatively low probability. Therefore, early containment failures for the transient PDSG are determined from just the failure to isolate event.

Containment failure at vessel breach includes in-vessel steam explosions, ex-vessel steam explosions, overpressurization at vessel breach, and direct impingement events. These events, except for in-vessel steam explosion, appear in every SCET. In-vessel steam explosion does not appear in the transient tree because of its low probability in this PDSG.

Late containment failures nominally occur during the initial part of CCI, and are explicitly represented on each SCET except transient, again, because of the extremely low probability of occurrence for this group.

Very late failures occur 12 to 24 hours after vessel breach and are explicitly represented in all SCETs. Therefore, the binner references this event directly.

The last possibility for the containment failure time characteristic is no containment failure. This event collects all SCET endstates not assigned one of the previous dimensions.

Sprays. The second source term characteristic is the *operability of containment sprays*. To keep the trees simple, containment spray function was not included as a SCET event when it was possible to capture the timeframe for spray operation through binning assumptions, or through correlation with other SCET events. In the SBO trees, spray operability is assumed to follow the availability of ac power. However, this assumption did not allow the modeling of option B—spray operation in the early and intermediate timeframe. Correlating spray operation with ac power availability introduces some error because a small number of scenarios exist where hydrogen detonations or steam explosions damage the spray system and prevent its operation when power is later recovered.

In the LOCA SCET, containment spray function during core degradation and during the period following vessel breach are included as top events. This allows modeling of spray options A, D, F, and H with reasonable accuracy. The remaining attributes are not explicitly accounted for because they are relatively unlikely and could not be modeled properly with the level of detail available in the SCET.

In the transient and ATWS trees, the sprays are assumed to be available for all pathways up to the time of vessel breach. After vessel breach, containment spray is questioned explicitly because its continued availability depends on the occurrence of energetic events at the time of vessel breach. Only options A and D were accounted for in the source term binning. As above, the remaining attributes were excluded from consideration because of their relative insignificance (consequently, the SCETs for these plant damage state groups lack sufficient detail to model them).

Core-Concrete Interactions. Characteristic 3, the *occurrence of core-concrete interaction*, was explicitly represented by a top event in all five SCETs. However, the SCETs were not developed in the same detail as the APETs in this respect, so some approximation was necessary to capture the necessary CCI attributes.

In the SBO SCET, attributes A, B, C, and D were modeled. Attribute A, *dry CCI that starts immediately*, was modeled as dependent on failure to restore ac power early, on failure to depressurize, on vessel breach, and on the prompt CCI event in the SB tree. Attribute B, *CCI that occurs under 5 ft of water*, was assumed to occur under the same conditions as attribute A, with the additional requirement that the reactor is depressurized before vessel breach. Attribute C, *no CCI*, was considered to occur when vessel breach is avoided, or when vessel breach is followed by the no CCI event in the SCET. Attribute D, *CCI under 10 ft of water*, picks up any pathways that include vessel breach, and CCI, but were not collected by the previous attributes.

The CCI attributes assigned to the LOCA, transient, and ATWS SCET pathways included only

C and D. The understanding here is that if CCI occurs at all, it will likely occur under a significant amount of water. This is because a large number of LOCA PDSG endstates went to core damage after a significant amount of water had been injected into the RCS. The logic for assigning transient and ATWS SCET endstates was similar.

RCS Pressure before Vessel Breach. The fourth characteristic, RCS pressure before vessel breach, appears explicitly in all SCETs. The SEQSOR program actually recognizes four pressure range attributes, more than can be accounted for using the simplified approach. However, in developing the SCETs, the RCS pressure is characterized as low, if it is below 200 psia, and high otherwise.

Station blackout, LOCA, and ATWS SCET pathways were assigned attribute B, *pressure between 1000–2000 psia*, if there was a failure to depressurize the RCS. If depressurization did occur, then attribute D, pressure less than 200 psia was assigned. Transient SCET pathways were assigned attribute A—*pressure at the system setpoint pressure*, if depressurization fails.

Mode of Vessel Breach. The next characteristic, *mode of vessel breach*, accounts for: HPME, molten debris pouring through a hole in the bottom of the vessel, complete bottom head failure, alpha or rocket failures, and no containment failure. Because alpha mode failures are accounted for explicitly in all the SCETS except transient, where it is a very low probability event, the binner can account for this attribute directly. Of the remaining possibilities, the assumption is made that if vessel failure occurs, it will be a pour–type event. The SEQSOR program does not refer to this characteristic in calculating a release, so the approximations made here have no effect on the consequence analysis. This characteristic is required as a place holder, and for comparison with published source term bin data.

In SBO and LOCA, attribute A was assigned if depressurization failed and vessel breach occurred, but IVSE did not. Attribute B was assigned if depressurization was successful. Attribute D was assigned to paths that included alpha mode failures (event IVSE), and attribute F was assigned to the remaining pathways. The transient and ATWS SCETs were treated similarly, except that IVSE was not accounted for.

Steam Generator Tube Rupture. Characteristic six, *steam generator tube rupture*, is accounted for directly in the trees were it occurs with a significant probability. However, this characteristic has three dimensions defining whether SGTR occurs with or without stuck–open SG SRVs. The binner assumes that if SGTR occurs, the SRVs will not stick open. This is nonconservative with respect to release timing, but consistent with the fact that the conditional probability of a stuck–open SRV is quite low.

SGTR does not occur at all in the SBO and LOCA SCETs, therefore all pathways are assigned attribute C. The transient and ATWS SCETS include SGTR events, and pathways where this event occurs are assigned attribute A, *SGTR with secondary RVs reclosing*. Otherwise attribute C, *no* SGTR, is assigned.

Amount of Core Not in HPME Available for CCI. Characteristic seven, *the amount of core not involved in HPME that is available for CCI*, is not directly addressed in any of the SCETs. Examination of the APET output shows that most of the pathways through the APET that have CCI involve 0–30% of the core.

SBO, LOCA, and ATWS SCETs are given a conservative treatment of the amount of core available for CCI. That is, if CCI occurs, it is assumed to involve 70–100% of the core. Transient SCET endstates are assumed to have option–B, 0–30% of core involved, if CCI occurs.

Zr Oxidation. Characteristic eight, *the amount of Zr oxidation in–vessel*, was also not addressed by the SCETs. However the majority of scenarios in the APETs experienced low (0–40%, nominal value of 25%) oxidation, so all SCET endstates were assigned this dimension for characteristic eight.

High Pressure Melt Ejection. Characteristic nine, *the fraction of core that was ejected* *under pressure at vessel breach*, was not addressed in the SCETs. The assumption, based on frequency output data from the APET, was that when the vessel is breached at high pressure, greater than 40% is involved in HPME. Otherwise HPME is assumed not to occur.

Containment Failure Size. Characteristic 10, *containment failure size*, is not explicitly addressed by the SCETs, but is closely related to containment failure mode, which is addressed. Attribute A, *catastrophic rupture*, is assigned to paths with hydrogen burns, failures at vessel breach, and late overpressure failures. Attribute B, *ruptures characterized by a hole larger than 7 ft^2*, is assigned to paths with ex–vessel steam explosions and very late containment failures. Attribute C, *leakage*, is associated with failure to isolate, direct impingement failures, and very late containment failures (when dominated by basemat melt–through instead of overpressure). Attribute D, *no containment failure*, is assigned to pathways not covered by one of the above assignments.

Holes in the RCS. Characteristic 11, *the number of holes in the RCS*, is strongly correlated with alpha or rocket failures. Should a pathway through the SCET include an IVSE event it is assigned the 2–Hole attribute of this characteristic, otherwise it is assigned the one–hole attribute.

Early Ice Condenser Function. Characteristic 12, *early ice condenser function*, is addressed directly in the station blackout SCETs. If early ice bypass occurs, it is assigned attribute C, *total ice bypass or melting*. Attribute B is not utilized in the SCET source term binning. In the remaining SCETs, early ice bypass is so unlikely that attribute A, no ice bypass, is assigned to all pathways.

Late Ice Condenser Function. Characteristic 13, *late ice condenser function*, is addressed directly in the station blackout SCETs. If late ice bypass occurs, it is assigned attribute C, *total ice bypass*. In the transient SCET, late ice bypass is correlated with ex–vessel steam explosion. If IVSE occurs, attribute C is assigned to the pathway. In the LOCA and ATWS trees, all paths are assigned attribute A, *no ice bypass*.

Status of Air Return Fans. Characteristic 14, *status of air return fans*, is correlated with the availability of ac power in the blackout trees. In the LOCA SCET, attribute A, *operation only in the early timeframe*, is assigned if there are no hydrogen–burn–induced early failures, and the vessel is later breached. Attribute B is assigned if there are no burns, and there is no vessel breach. Attribute C is never assigned, and attribute D is assigned to the remaining paths.

In the transient SCET, air return fans are assumed to always be operable in the early timeframe. After vessel breach, they are assumed to be operable unless an ex–vessel steam explosion occurs, or unless overpressure at VB occurs. In the ATWS SCET, similar logic is applied. The fans are assumed to be operable unless disabled by a hydrogen burn during the early timeframe.

4.3.2 Source Term Calculation for Each Release Mode. Applying the binning scheme described above to each of the SCETs endstates resulted in the definition of 464 unique source term bins. These bins, each described by a 14–character vector, are passed to the SEQSOR program and it calculates a source term for each. These release source terms are then processed with the PARTITION code, which generates and plots each source term on a consequence grid. In addition to calculating an estimate of the early and latent fatalities for each source term, PARTITION also divides the source terms into two release categories.

The first release category includes those releases with both an early and latent fatality potential. The second includes those with only latent fatality potential. The PARTITION grid chosen for the SCET analysis is shown in Figure 7. Both the number of source terms and the combined frequency for each cell on the grid are presented. Grid locations associated with a very low frequency are repooled with adjacent grids, resulting in even fewer source terms that must be evaluated. After repooling, the arrangement in Figure 8 results. Note that there are only 11 nonzero

CELL COUNTS WITHIN THE GRID FOR A TOTAL COUNT OF 294:

	1	2	3	4	5	6	7	8
1								12
2						58	51	1
3					1	40		
4				8	36	4		
5			3	24	7			
6	4	23	22					

PERCENTAGE OF WEIGHTED FREQUENCIES CONTAINED IN EACH CELL:

	1	2	3	4	5	6	7	8
1								1.83
2						6.73	8.69	2.80
3					0.00	27.41		
4				0.63	34.77	0.41		
5			1.69	1.02	0.45			
6	0.08	7.31	6.17					

Figure 7. Distribution of source terms before repooling.

CELL COUNTS WITHIN THE GRID FOR A TOTAL COUNT OF 294:

	1	2	3	4	5	6	7	8
1								12
2						58	51	1
3						45		
4				9	42			
5			3	24				
6		27	22					

PERCENTAGE OF WEIGHTED FREQUENCIES CONTAINED IN EACH CELL:

	1	2	3	4	5	6	7	8
1								1.83
2						6.73	8.69	2.80
3						27.81		
4				0.74	35.12			
5			1.69	1.02				
6		7.39	6.17					

Figure 8. Source term distribution after repooling.

groups with both early and latent fatality potential that require source term analysis.

A similar process is done for source terms that have the potential for producing only latent cancers. The result before and after repooling is shown in Figure 9. The process creates four additional source term groups. Figure 10 shows how each source term group resulting from the partitioning process is identified in the remainder of the analysis.

The 15 groups are each further divided into three subgroups on the basis of evacuation timing. The first subgroup includes releases in which evacuation is started 30 min before the first plume segment is released. Individuals evacuating in this timeframe are assumed to escape radiation exposure from the release. The second subgroup includes releases where evacuation is started too late for individuals to completely escape the first release segment, but within one hour of the beginning of the release. The final group includes releases where evacuation is started later than one hour after the beginning of the first release segment.

The assignment of releases to subgroups is made on the basis of the evacuation warning time (TW) calculated by SEQSOR, and on the evacuation delay time (2.3 hours). The evacuation warning time is generally the time at which core

CELL COUNTS WITHIN THE GRID FOR A TOTAL COUNT OF 170:

BEFORE POOLING

	1	2	3	4	5
1	59	1	48	50	12

PERCENTAGE OF WEIGHTED FREQUENCIES CONTAINED IN EACH CELL:

	1	2	3	4	5
1	73.28	0.02	25.85	0.71	0.14

AFTER POOLING

	1	2	3	4	5
1	59		49	50	12

PERCENTAGE OF WEIGHTED FREQUENCIES CONTAINED IN EACH CELL:

	1	2	3	4	5
1	73.28		25.86	0.71	0.14

Figure 9. Source term (for zero early fatality potential source terms) distribution before and after repooling.

SOURCE TERM GROUP IDENTIFIERS

	1	2	3	4	5	6	7	8
1								SEQ-10
2						SEQ-07	SEQ-09	SEQ-11
3						SEQ-08		
4				SEQ-04	SEQ-06			
5			SEQ-02	SEQ-05				
6		SEQ-01	SEQ-03					

	1	2	3	4	5
1	SEQ-12		SEQ-13	SEQ-14	SEQ-15

Figure 10. Source term group identifiers.

collapse occurs. In V–sequences, and sequences with containment failure before core damage, the evacuation warning time is the time of core uncovery. Using the PARTITION logic for separating subgroups, and the warning and release times calculated in the SEQSOR program, provides the following assignment of release bins to release subgroups. Bins with no containment failure, with containment failure in the late or very late periods, with steam generator tube rupture and secondary SRVs stuck open all go to subgroup one. Steam generator tube ruptures and containment failures at or before vessel breach are assigned to subgroup two. Only V–sequences are assigned to subgroup three (therefore there are no group–three assignments resulting from SCET analysis). The source term data resulting from this step of the process is presented in Table 10.

4.3.3 Consequence Calculation. The source terms produced from the PARTITION runs are used as inputs to the MACCS code to generate consequence measures. For the SCET development, the consequence vectors include early fatalities, latent cancer fatalities, and 50–mile population dose. A PC–based version of the code is available and was used in the present analysis.[a] The MACCS input files that contain the site characteristic data and dose data were those used in the NUREG–1150 Sequoyah analysis. These files were modified only as necessary to be compatible with the PC version of the code, which is a later release than was used in the NUREG–1150 analyses. The fission product releases were provided by the SEQSOR program described in the previous section, with format translation provided by the STER program.[b]

a. Information was taken from "Documentation of INEL PC Version of MACCS 1.5.11, INEL Calculation Package," dated November 3, 1989, and done by K. R. Jones, EG&G Idaho, Inc.

b. The STER program is an undocumented translation code that is not strictly necessary to the analysis. It can be obtained from Sandia National Laboratory (SNL) along with the other level 2 and 3 analysis codes as described in Section 3.

Table 10. Sequoyah source term data by PARTITION group and subgroup

Source Term	Warning Time (s)	Evac Time (s)	Elevation (m)	Energy (w)	Start (s)	Duration (s)	Release Fractions NG	I	CS	Te	Sr	Ru	La	Ce	Ba
SEQ-01	2.2E+04	-2.6E+03	1.0E+01	1.7E+07	2.8E+04	6.8E+02	8.3E-01	3.9E-03	3.9E-03	1.7E-03	5.5E-04	4.0E-04	1.1E-04	1.1E-04	6.0E-04
				5.0E+05	3.3E+05	3.2E+05	1.7E-01	7.2E-04	7.2E-04	5.5E-04	4.2E-04	1.4E-04	5.5E-05	5.0E-05	3.1E-04
SEQ-01-1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-01-2	2.2E+04	-2.6E+03	1.0E+01	1.7E+07	2.8E+04	6.8E+02	8.3E-01	3.9E-03	3.9E-03	1.7E-03	5.5E-04	4.0E-04	1.1E-04	1.1E-04	6.0E-04
				5.0E+05	3.3E+05	3.2E+05	1.7E-01	7.2E-04	7.2E-04	5.5E-04	4.2E-04	1.4E-04	5.5E-05	5.0E-05	3.1E-04
SEQ-01-3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-02	2.2E+04	-2.6E+03	1.0E+01	5.2E+05	2.8E+04	1.0E+03	7.5E-01	3.9E-03	3.9E-03	1.7E-03	5.2E-04	6.2E-04	1.7E-04	1.7E-04	6.0E-04
				1.6E+06	2.9E+04	2.2E+04	2.5E-01	1.3E-03	1.3E-03	6.8E-03	1.3E-02	2.1E-04	8.0E-04	6.1E-04	7.7E-03
SEQ-02-1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-02-2	2.2E+04	-2.6E+03	1.0E+01	5.2E+05	2.8E+04	1.0E+03	7.5E-01	3.9E-03	3.9E-03	1.7E-03	5.2E-04	6.2E-04	1.7E-04	1.7E-04	6.0E-04
				1.6E+06	2.9E+04	2.2E+04	2.5E-01	1.3E-03	1.3E-03	6.8E-03	1.3E-02	2.1E-04	8.0E-04	6.1E-04	7.7E-03
SEQ-02-3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-03	2.2E+04	-2.6E+03	1.0E+01	3.3E+07	2.8E+04	7.9E+02	9.0E-01	7.1E-03	7.1E-03	2.5E-03	8.3E-04	4.0E-05	1.1E-05	1.1E-05	8.4E-04
				7.4E+05	1.3E+05	1.2E+05	9.7E-02	1.2E-03	1.2E-03	1.8E-03	7.6E-04	2.9E-06	3.7E-05	2.8E-05	5.0E-04
SEQ-03-1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-03-2	2.2E+04	-2.6E+03	1.0E+01	3.3E+07	2.8E+04	7.9E+02	9.0E-01	7.1E-03	7.1E-03	2.5E-03	8.3E-04	4.0E-05	1.1E-05	1.1E-05	8.4E-04
				7.4E+05	1.3E+05	1.2E+05	9.7E-02	1.2E-03	1.2E-03	1.8E-03	7.6E-04	2.9E-06	3.7E-05	2.8E-05	5.0E-04
SEQ-03-3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-04	2.2E+04	-2.6E+03	1.0E+01	4.8E+07	2.8E+04	1.5E+03	1.0E+00	3.0E-02	2.7E-02	2.4E-02	3.6E-03	6.7E-03	1.8E-03	1.8E-03	4.4E-03
				1.4E+06	7.8E+05	7.8E+05	0.0E+00	0.0E+00	0.0E+00	1.5E-05	1.9E-05	8.1E-10	1.1E-06	8.5E-07	1.1E-05
SEQ-04-1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-04-2	2.2E+04	-2.6E+03	1.0E+01	4.8E+07	2.8E+04	1.5E+03	1.0E+00	3.0E-02	2.7E-02	2.4E-02	3.6E-03	6.7E-03	1.8E-03	1.8E-03	4.4E-03
				1.4E+06	7.8E+05	7.8E+05	0.0E+00	0.0E+00	0.0E+00	1.5E-05	1.9E-05	8.1E-10	1.1E-06	8.5E-07	1.1E-05
SEQ-04-3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-05	2.2E+04	-2.6E+03	1.0E+01	2.0E+06	2.8E+04	1.3E+03	7.9E-01	1.4E-02	1.4E-02	5.0E-03	1.9E-03	9.6E-04	2.6E-04	2.6E-04	2.0E-03
				1.2E+06	8.0E+04	7.3E+04	2.1E-01	3.2E-03	3.2E-03	1.3E-02	2.8E-03	1.8E-04	1.9E-04	1.5E-04	1.9E-03
SEQ-05-1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-05-2	2.2E+04	-2.6E+03	1.0E+01	2.0E+06	2.8E+04	1.3E+03	7.9E-01	1.4E-02	1.4E-02	5.0E-03	1.9E-03	9.6E-04	2.6E-04	2.6E-04	2.0E-03
				1.2E+06	8.0E+04	7.3E+04	2.1E-01	3.2E-03	3.2E-03	1.3E-02	2.8E-03	1.8E-04	1.9E-04	1.5E-04	1.9E-03
SEQ-05-3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Table 10. (continued)

Source Term	Warning Time (s)	Evac. Time (s)	Elevation (m)	Energy (w)	Start (s)	Duration (s)	Release Fractions NG	I	CS	Te	Sr	Ru	La	Ce	Ba
SEQ-06	2.2E+04	-2.6E+03	1.0E+01	2.2E+08 8.1E+05	2.8E+04 4.7E+05	3.5E+01 4.7E+05	1.0E+00 2.2E-03	3.6E-02 9.9E-05	3.6E-02 9.9E-05	3.5E-02 7.1E-04	5.8E-03 1.0E-03	6.5E-03 2.7E-08	1.8E-03 5.8E-05	1.8E-03 4.3E-05	6.5E-03 5.9E-04
SEQ-06-1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-06-2	2.2E+04	-2.6E+03	1.0E+01	2.2E+08 8.1E+05	2.8E+04 4.7E+05	3.5E+01 4.7E+05	1.0E+00 2.2E-03	3.6E-02 9.9E-05	3.6E-02 9.9E-05	3.5E-02 7.1E-04	5.8E-03 1.0E-03	6.5E-03 2.7E-08	1.8E-03 5.8E-05	1.8E-03 4.3E-05	6.5E-03 5.9E-04
SEQ-06-3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-07	1.3E+04	-1.1E+03	1.0E+01	3.9E+06 1.6E+03	2.0E+04 8.3E+05	3.1E+03 8.2E+05	4.2E-01 2.2E-02	1.5E-01 2.9E-03	1.5E-01 2.9E-03	2.3E-01 5.2E-03	2.2E-02 5.5E-04	1.8E-07 1.1E-08	1.8E-08 7.1E-06	1.8E-08 5.3E-06	2.2E-02 5.1E-04
SEQ-07-1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-07-2	1.3E+04	-1.1E+03	1.0E+01	3.9E+06 1.6E+03	2.0E+04 8.3E+05	3.1E+03 8.2E+05	4.2E-01 2.2E-02	1.5E-01 2.9E-03	1.5E-01 2.9E-03	2.3E-01 5.2E-03	2.2E-02 5.5E-04	1.8E-07 1.1E-08	1.8E-08 7.1E-06	1.8E-08 5.3E-06	2.2E-02 5.1E-04
SEQ-07-3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-08	2.2E+04	-2.6E+03	1.0E+01	4.4E+08 6.6E+05	2.8E+04 3.3E+05	3.1E+01 3.3E+05	1.0E+00 0.0E+00	1.0E-01 0.0E+00	1.0E-01 0.0E+00	3.4E-02 9.6E-03	1.3E-02 5.0E-03	1.8E-03 1.7E-07	4.8E-04 2.9E-04	4.8E-04 2.2E-04	1.3E-02 2.9E-03
SEQ-08-1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-08-2	2.2E+04	-2.6E+03	1.0E+01	4.4E+08 6.6E+05	2.8E+04 3.3E+05	3.1E+01 3.3E+05	1.0E+00 0.0E+00	1.0E-01 0.0E+00	1.0E-01 0.0E+00	3.4E-02 9.6E-03	1.3E-02 5.0E-03	1.8E-03 1.7E-07	4.8E-04 2.9E-04	4.8E-04 2.2E-04	1.3E-02 2.9E-03
SEQ-08-3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-09	2.2E+04	-2.6E+03	1.0E+01	4.8E+08 1.4E+06	2.8E+04 3.8E+05	3.2E+01 3.8E+05	1.0E+00 2.3E-03	2.5E-01 3.2E-04	2.5E-01 3.2E-04	6.7E-02 2.0E-03	2.9E-02 4.9E-04	1.3E-04 3.4E-06	3.6E-05 2.7E-05	3.6E-05 2.1E-05	2.9E-02 3.0E-04
SEQ-09-1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-09-2	2.2E+04	-2.6E+03	1.0E+01	4.8E+08 1.4E+06	2.8E+04 3.8E+05	3.2E+01 3.8E+05	1.0E+00 2.3E-03	2.5E-01 3.2E-04	2.5E-01 3.2E-04	6.7E-02 2.0E-03	2.9E-02 4.9E-04	1.3E-04 3.4E-06	3.6E-05 2.7E-05	3.6E-05 2.1E-05	2.9E-02 3.0E-04
SEQ-09-3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-10	2.2E+04	-2.6E+03	1.0E+01	4.1E+08 3.4E+05	2.8E+04 1.0E+05	1.9E+01 9.3E+04	1.0E+00 0.0E+00	7.6E-01 0.0E+00	7.6E-01 0.0E+00	2.0E-01 4.1E-02	8.9E-02 8.6E-03	6.8E-07 4.8E-07	6.8E-08 5.1E-04	6.8E-08 3.8E-04	8.9E-02 5.1E-03
SEQ-10-1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-10-2	2.2E+04	-2.6E+03	1.0E+01	4.1E+08 3.4E+05	2.8E+04 1.0E+05	1.9E+01 9.3E+04	1.0E+00 0.0E+00	7.6E-01 0.0E+00	7.6E-01 0.0E+00	2.0E-01 4.1E-02	8.9E-02 8.6E-03	6.8E-07 4.8E-07	6.8E-08 5.1E-04	6.8E-08 3.3E-04	8.9E-02 5.1E-03
SEQ-10-3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ-11	2.2E+04	-2.6E+03	1.0E+01	5.6E+07 1.6E+05	2.8E+04 1.0E+06	1.0E+01 1.0E+06	1.0E+00 0.0E+00	4.0E-01 0.0E+00	4.0E-01 0.0E+00	1.0E-01 0.0E+00	4.7E-02 0.0E+00	3.6E-07 0.0E+00	3.6E-08 0.0E+00	3.6E-08 0.0E+00	4.7E-02 0.0E+00

Table 10. (continued)

Source Term	Warning Time (s)	Evac. Time (s)	Elevation (m)	Energy (w)	Start (s)	Duration (s)	Release Fractions NG	I	CS	Te	Sr	Ru	La	Ce	Ba
SEQ–11–1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ–11–2	2.2E+04	-2.6E+03	1.0E+01	5.6E+07	2.8E+04	1.0E+01	1.0E+00	4.0E–01	4.0E–01	1.0E–01	4.7E–02	3.6E–07	3.6E–08	3.6E–08	4.7E–02
				1.6E+05	1.0E+06	1.0E+06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
SEQ–11–3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ–12	2.2E+04	1.6E+04	0.0E+00	0.0E+00	4.7E+04	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
				0.0E+00	4.7E+04	8.6E+04	5.0E–03	5.8E–09	5.8E–09	1.4E–09	7.7E–10	8.4E–15	4.4E–12	3.3E–12	7.4E–10
SEQ–12–1	2.2E+04	1.6E+04	0.0E+00	0.0E+00	4.7E+04	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
				0.0E+00	4.7E+04	8.6E+04	5.0E–03	5.8E–09	5.8E–09	1.4E–09	7.7E–10	8.4E–15	4.4E–12	3.3E–12	7.4E–10
SEQ–12–2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ–12–3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ–13	2.2E+04	1.6E+04	1.0E+01	0.0E+00	4.7E+04	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
				1.4E+07	1.2E+05	1.0E+03	1.0E+00	1.7E–06	1.7E–06	6.0E–05	1.4E–05	8.5E–10	8.4E–07	6.3E–07	8.5E–06
SEQ–13–1	2.2E+04	1.6E+04	1.0E+01	0.0E+00	4.7E+04	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
				1.4E+07	1.2E+05	1.0E+03	1.0E+00	1.7E–06	1.7E–06	6.0E–05	1.4E–05	8.5E–10	8.4E–07	6.3E–07	8.5E–06
SEQ–13–2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ–13–3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ–14	2.2E+04	4.4E+03	1.0E+01	3.3E+04	3.5E+04	5.6E+03	6.0E–01	3.9E–04	3.9E–04	1.0E–04	4.6E–05	3.6E–10	3.6E–11	3.6E–11	4.6E–05
				3.5E+07	5.3E+05	5.1E+05	4.0E–01	4.4E–05	4.4E–05	1.2E–03	2.4E–04	1.4E–08	1.4E–05	1.0E–05	1.4E–04
SEQ–14–1	2.2E+04	4.4E+03	1.0E+01	3.3E+04	3.5E+04	5.6E+03	6.0E–01	3.9E–04	3.9E–04	1.0E–04	4.6E–05	3.6E–10	3.6E–11	3.6E–11	4.6E–05
				3.5E+07	5.3E+05	5.1E+05	4.0E–01	4.4E–05	4.4E–05	1.2E–03	2.4E–04	1.4E–08	1.4E–05	1.0E–05	1.4E–04
SEQ–14–2	2.2E+04	4.4E+03	1.0E+01	3.3E+04	3.5E+04	5.6E+03	6.0E–01	3.9E–04	3.9E–04	1.0E–04	4.6E–05	3.6E–10	3.6E–11	3.6E–11	4.6E–05
				3.5E+07	5.3E+05	5.1E+05	4.0E–01	4.4E–05	4.4E–05	1.2E–03	2.4E–04	1.4E–08	1.4E–05	1.0E–05	1.4E–04
SEQ–14–3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SEQ–15	2.2E+04	1.5E+04	1.0E+01	4.2E+03	4.5E+04	8.7E+02	8.1E–02	2.1E–04	2.1E–04	7.9E–05	2.4E–05	1.8E–10	1.8E–11	1.8E–11	2.4E–05
				6.4E+08	1.2E+05	8.1E+04	9.2E–01	1.0E–02	1.0E–02	6.8E–03	2.0E–03	8.2E–08	4.8E–05	3.6E–05	1.7E–03
SEQ–15–1	2.2E+04	1.5E+04	1.0E+01	4.2E+03	4.5E+04	8.7E+02	8.1E–02	2.1E–04	2.1E–04	7.9E–05	2.4E–05	1.8E–10	1.8E–11	1.8E–11	2.4E–05
				6.4E+08	1.2E+05	8.1E+04	9.2E–01	1.0E–02	1.0E–02	6.8E–03	2.0E–03	8.2E–08	4.8E–05	3.6E–05	1.7E–03
SEQ–15–2	2.2E+04	1.5E+04	1.0E+01	4.2E+03	4.5E+04	8.7E+02	8.1E–02	2.1E–04	2.1E–04	7.9E–05	2.4E–05	1.8E–10	1.8E–11	1.8E–11	2.4E–05
				6.4E+08	1.2E+05	8.1E+04	9.2E–01	1.0E–02	1.0E–02	6.8E–03	2.0E–03	8.2E–08	4.8E–05	3.6E–05	1.7E–03
SEQ–15–3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

The results of the consequence calculations are summarized by source term group in Table 11. Table 12 shows the spreadsheet layout used to calculate risk from the consequence and frequency data.

4.3.4 Comparison with Draft NUREG-1150. The risk calculated with the SCETs is compared against the Sequoyah NUREG-1150 data in Table 13. Agreement is generally good considering the uncertainty distributions in the NUREG-1150 calculation. Early fatalities are consistently underestimated with the SCETs. It is likely that further sensitivity calculations would pinpoint the source of this bias, however, time and resource constraints did not permit this. Because the containment failure mode calculations are in very close agreement with the NUREG-1150 results, the source of the difference is most likely within either the source term (i.e. some non-conservatisms might have been introduced in generating the 14-character vector) or consequence calculation (newer version of MACCS was used). This same problem was encountered in Reference 15 (Zion CPIP). There the difference was atributed primarily to the use of the central estimates in the SCET approach, as opposed to distributed parameters used in the NUREG-1150 work.

Table 11. Consequence data presented by release group and subgroup

Group	Early Fatalities	Latent Fatalities	50 mi Dose (Rem)	1000 mi Dose (Rem)
SEQ-01-1 SEQ-01-2 SEQ-01-3	2.07E-05	2.73E+02	3.54E+05	1.60E+06
SEQ-02-1 SEQ-02-2 SEQ-02-3	1.16E-02	3.00E+02	5.47E+05	1.93E+06
SEQ-03-1 SEQ-03-2 SEQ-03-3	5.22E-08	4.14E+02	4.34E+05	2.40E+06
SEQ-04-1 SEQ-04-2 SEQ-04-3	6.11E-04	8.81E+02	7.04E+05	5.10E+06
SEQ-05-1 SEQ-05-2 SEQ-05-3	7.80E-03	6.21E+02	7.41E+05	3.64E+06
SEQ-06-1 SEQ-06-2 SEQ-06-3	2.63E-04	1.15E+03	5.55E+05	6.83E+06

Table 11. (continued)

Group	Early Fatalities	Latent Fatalities	50 mi Dose (Rem)	1000 mi Dose (Rem)
SEQ-07-1				
SEQ-07-2	1.95E+00	2.01E+03	1.64E+06	1.17E+07
SEQ-07-3				
SEQ-08-1				
SEQ-08-2	6.74E-04	2.07E+03	7.17E+05	1.24E+07
SEQ-08-3				
SEQ-09-1				
SEQ-09-2	5.52E-03	3.26E+03	9.07E+05	1.96E+07
SEQ-09-3				
SEQ-10-1				
SEQ-10-2	1.57E+00	6.08E+03	1.68E+06	3.66E+07
SEQ-10-3				
SEQ-11-1				
SEQ-11-2	4.18E+00	3.96E+03	1.66E+06	2.37F+07
SEQ-11-3				
SEQ-12-1	0.00E+00	5.40E-03	8.38E+00	3.22E+01
SEQ-12-2				
SEQ-12-3				
SEQ-13-1	0.00E+00	1.94E+00	3.28E+03	1.20E+04
SEQ-13-2				
SEQ-13-3				
SEQ-14-1	0.00E+00	[illegible]	3.74E+04	2.16E+05
SEQ-14-2	9.40E-06	4.14E+01	9.38E+04	2.39E+05
SEQ-14-3				
SEQ-15-1	1.86E-06	5.29E+02	2.41E+05	3.09E+06
SEQ-15-2	2.63E-05	1.24E+02	2.29E+05	7.19E+05
SEQ-15-3				

Table 12. Sequoyah SCET risk results for five PDSGs

Source Term Grid	SBO–LT PDSG–1 4.6E–06	SBO–ST PDSG–2 9.3E–06	LOCA PDSG–3 3.5E–05	Trans PDSG–5 2.4E–06	ATWS PDSG-6 2. E–06	Cond. 50–mile Pop Dose	50–mile Pop Dose Risk	Cond. Early Fatal.	Early Fatal. Risk	Cond. Latent Cancers	Latent Cancer Risk
1–2	1.1E–02	1.9E–02	2.6E–03	1.1E–04	5.6E–03	3.5E+05	1.2E–01	2.1E–05	6.8E–12	2.7E+02	9.0E–05
2–2	7.0E–03	4.6E–03				5.5E+05	4.1E–02	1.2E–02	8.8E–10	3.0E+02	2.3E–05
3–2	4.8E–03	9.6E–03	3.3E–03	4.1E–03	1.8E–02	4.3E+05	1.2E–01	5.2E–08	1.4E–14	4.1E+02	1.1E–04
4–2			1.3E–04	1.2E–02		7.0E+05	2.4E–02	6.1E–04	2.1E–11	8.8E+02	3.0E–05
5–2	2.6E–03	2.6E–03	1.8E–04		1.5E–03	7.4E+05	3.4E–02	7.8E–03	3.5E–10	6.2E+02	2.8E–05
6–2	4.8E–02	5.1E–02	2.4E–02	5.8E–05	1.9E–02	5.6E+05	8.7E–01	2.6E–04	4.1E–10	1.2E+03	1.8E–03
7–2		1.7E–04		6.4E–03	1.3E–01	1.6E+06	4.9E–01	1.9E+00	5.8E–07	2.0E+03	6.0E–04
8–2	5.5E–02	8.1E–02	6.5E–03	2.9E–07	5.3E–04	7.2E+05	8.9E–01	6.7E–04	8.3E–10	2.1E+03	2.6E–03
9–2	3.4E–03	2.6E–03	9.5E–03	6.9E–05	2.0E–03	9.1E+05	3.4E–01	5.5E–03	2.1E–09	3.3E+03	1.2E–03
10–2	2.7E–03	7.4E–03				1.7E+06	1.4E–01	1.6E+00	1.3E–07	6.1E+03	5.0E–04
11–2	1.1E–02	8.0E–03				1.7E+06	2.1E–01	4.2E+00	5.2E–07	4.0E+03	4.9E–04
12–1	7.1E–01	5.5E–01	6.8E–01	9.3E–01	6.6E–01	8.4E+00	3.0E–04	0.0E+00	0.0E+00	5.4E–03	1.9E–07
13–1	1.4E–01	2.4E–01	2.7E–01	3.9E–02	1.5E–01	3.3E+03	4.1E–02	0.0E+00	0.0E+00	1.9E+00	2.5E–05
14–1	1.4E–03	1.3E–02	1.0E–04		6.8E–04	3.7E+04	4.8E–03	0.0E+00	0.0E+00	3.3E+01	4.2E–06
14–2	3.0E–03	1.5E–03	4.8E–03	5.6E–03	4.4E–03	9.4E+04	2.1E–02	9.4E–06	2.1E–12	4.1E+01	9.1E–06
15–1	4.3E–03	3.0E–03	1.5E–04			2.4E+05	1.3E–02	1.9E–06	9.8E–14	5.3E+02	2.8E–05
15–2	9.8E–05	8.7E–05	4.4E–04	4.9E–05	5.9E–04	2.3E+05	4.2E–03	2.6E–05	4.8E–13	1.2E+02	2.3E–06
	1.00E+00	9.99E–01	9.99E–01	1.00E+00	1.00E+00		3.35E+00		1.24E–06		7.52E–03
					SBO–LT PDSG–1		4.87E–01		2.34E–07		1.16E–03
					SBO–ST PDSG–2		1.23E+00		4.22E–07		3.04E–03
					LOCA PDSG–3		1.06E+00		2.26E–09		2.61E–03
					Trans PDSG–5		5.20E–02		3.02E–08		6.23E–05
					ATWS PDSG–6		5.14E–01		5.49E–07		6.50E–04
							3.35E+00		1.24E–06		7.52E–03

Table 13. SCET risk results compared to Draft NUREG-1150 risk results (FCMR and MFCR methods utilize APETs and are from NUREG/CR-4551, Vol.5, Table 5.1-2)

PDS Group	Method	Core Damage Frequency	50-Mile Population Dose	Early Fatalities	Latent Cancers
SBO-LT	FCMR[a]	4.6E-06	1.3E+00	1.8E-06	1.8E-03
PDSG-1	MFCR[b]	4.5E-06	9.6E-01	1.7E-06	1.2E-03
	SCET	N/A	4.9E-01	2.3E-07	1.2E-03
SBO-ST	FCMR	9.3E-06	3.2E+00	4.2E-06	4.0E-03
PDSG-2	MFCR	9.4E-06	2.9E+00	4.7E-06	3.6E-03
	SCET	N/A	1.2E+00	4.2E-07	3.0E-03
LOCA	FCMR	3.5E-05	2.2E+00	4.4E-07	2.0E-03
PDSG-3	MFCR	3.4E-05	3.4E+00	3.4E-06	2.9E-03
	SCET	N/A	1.1E+00	2.3E-09	2.6E-03
Event-V	FCMR	6.7E-07	1.8E+00	1.8E-05	1.4E-03
PDSG-4	MFCR	8.4E-07	1.2E+00	1.1E-05	1.4E-03
Trans	FCMR	2.4E-06	6.0E-02	2.6E-08	7.0E-05
PDSG-5	MFCR	3.2E-06	1.6E-01	3.4E-07	2.0E-04
	SCET	N/A	5.2E-02	3.0E-08	6.2E-05
ATWS	FCMR	2.1E-06	4.4E-01	4.9E-07	5.3E-04
PDSG-6	MFCR	2.4E-06	6.4E-01	1.6E-06	8.0E-04
	SCET	N/A	5.1E-01	5.4E-07	6.5E-04
SGTR	FCMR	1.7E-06	3.0E+00	1.4E-06	4.2E-03
PDSG-7	MFCR	2.0E-06	2.7E+00	3.5E-06	3.9E-03
ALL PDSGs	FCMR	5.6E-05	1.2E+01	2.6E-05	1.4E-02
	MFCR	5.6E-05	1.2E+01	2.6E-05	1.4E-02
5-PDSGs	FCMR	5.4E-05	7.2E+00	6.9E-06	8.3E-03
	MFCR	5.3E-05	8.0E+00	1.2E-05	8.7E-03
SCET Totals			3.4E+00	1.2E-06	7.5E-03

a. FCMR-fractional contribution to mean risk.

b. MFCR-mean fractional contribution to risk.

5. ANALYSIS OF POTENTIAL CONTAINMENT IMPROVEMENTS

Based on the risks estimated for Sequoyah reported in NUREG–1150, a number of potential containment modifications have been postulated for improving the performance of the ice condenser containment. These modifications include:

1. Providing a hydrogen mitigation system (igniters) that will function in a station blackout sequence (either a backup power supply or passive catalytic igniters).

2. Backup power to the igniters plus backup power to the containment recirculation fans.

3. High pressure melt ejection (HPME) mitigation to prevent containment failure caused by the direct impingement of core material on the instrumentation seal table (and subsequently the containment wall). This modification, as envisioned here, entails lining the containment wall in the area of the seal table with refractory material.

4. Reduce the probability of hydrogen burns by inerting the containment atmosphere.

Each of these modifications is examined with respect to its risk reduction potential using either the SCETs (mods 1 and 3), the full APET (mod 2), or by inference (mod 4, which is functionally identical to mod 1). The risk reduction potentials are estimated through idealized evaluations that assume the potential modification operates perfectly and is 100% reliable.

For comparison, a bounding analysis is presented here that estimates the cost associated with reducing the total NUREG–1150 risk (50–mile population dose) to zero. The total person–rem risk estimated by the NUREG–1150 analyses of Sequoyah is 12 person–rem per year (from NUREG/CR–4551, Vol.5, Table 5.1–2). At \$1,000 per person–rem and conservatively assuming a 40–year plant lifetime, yields a maximum modification cost of \$480,000.

The procedure for evaluating potential modifications starts with a review of the SCETs to identify those events affected by the modification and to estimate what that effect is. After revision, the SCETs are requantified and new source term bin probabilities are calculated. These conditional source term probabilities are then combined with the PDSG frequency and the conditional consequences attributed to each source term bin through matrix multiplication to produce an overall estimate of risk.

5.1 Backup Power to the Hydrogen Ignition System

This potential modification addresses the concern of hydrogen accumulation in the ice condenser containment during a postulated severe accident. The threat posed by this situation is that the accumulated hydrogen could ignite and produce an explosion of sufficient magnitude to fail the containment and thereby allow the release of radioactive material to the environment. Currently all ice condenser type containments are fitted with hydrogen mitigation systems that consist of igniters (glow plugs) dispersed through the containment (see Appendix A). However, these systems are ac powered and therefore will not be operable during a station blackout (SBO) event. Because SBO was identified in Draft NUREG–1150 as a significant contributor to core damage frequency and risk, hydrogen–induced–containment failures remain an important issue for ice condenser containments.

The risk reduction attributable to this potential modification was estimated utilizing the SCETs. Because ac power (and therefore the igniters) is already available for non–SBO sequences, only the SBO event trees were modified to model the effects of this option. Specifically, the effect of having igniters operable during a SBO was reflected in the SCET by setting the probabilities of early containment failure (event ECF) and late containment failure (event LCF) to zero. These events were utilized to reflect the effects of the improved hydrogen control because these containment failure events are dominated by hydrogen burns that fail containment. However, it is not completely accurate to set these events to zero because there should remain a small probability (1E–3) that the containment will fail from slow overpressurization in the early and late timeframes. In the current analysis, this consideration is neglected. The effect of this simplification will be a negligible overestimation of the potential modifications benefit. The risk reduction resulting from this improvement is summarized in Table 14.

5.2 Backup Power to the HIS and Air Recirculation Fans

This potential containment improvement addresses the same issue as the previously discussed modification, namely preventing hydrogen burns from failing the containment. This potential modification takes the more comprehensive approach of providing backup power to both the hydrogen igniters and the containment air recirculation fan system (ARFS). The ARFS is designed to circulate the containment atmosphere from the lower compartment, through the ice condenser, to the

Table 14. Risk comparison between base case and modification #1 (backup power to igniters), utilizing SCETs

Plant Damage State Group	50-Mile Population Dose (person–rem per reactor year)		Early Fatalities (per reactor year)		Latent Cancers (per reactor year)	
	Base Case	Mod–1	Base Case	Mod 1	Base Case	Mod–1
SBO–LT PDSG–1	0.487	0.255	2.33E–7	2.50E–9	1.16E–3	5.41E–4
SBO–ST PDSG–2	1.23	0.829	4.22E–7	7.18E–8	3.04E–3	1.95E–3
LOCA PDSG–3	1.07	1.07	2.31E–9	2.31E–9	2.64E–3	2.64E–3
Trans PDSG–5	0.052	0.052	3.02E–8	3.02E–8	6.23E–5	6.23E–5
ATWS PDSG–6	0.514	0.514	5.49E–7	5.49E–7	6.50E–4	6.5E–4
Totals	3.35	2.72	1.24E–6	6.56E–7	7.55E–3	5.85E–3

Notes: Totals are for the five PDSG for which SCETs have been developed and do not include the two containment bypass sequences (Event–V and SGTR).

upper compartment, and then back into the lower compartment.

Because the fans are not explicitly modeled in the SCETs, this modification was evaluated utilizing the full-sized APETs. The general approach taken in this analysis, which is explained in more detail in Appendix B, was to review each question of the APET and to modify those that address the failure of the igniters or fans because of a lack of ac power. The backup power was assumed to be perfectly reliable. However, other (not power related) failure mechanisms were retained as modeled in the base case APETs. Specifically, the igniters are assigned a failure probability of 0.01, which is attributed to the failure of the operators to actuate the system. The ARFS is assumed to have a failure probability of 0.001 from system hardware faults. Both of these failure mechanisms were maintained for this sensitivity case.

The risk reduction attributed to this potential modification is shown below on Table 15. As can be seen this option is estimated to provide minimal benefit (less than 2 person–rem per reactor year) and would not likely be justified as a backfit.

5.3 High Pressure Melt Ejection Mitigation

Vessel failure at high RCS pressures can result in the rapid ejection of the molten core material. The molten core could travel through the instrumentation tunnel and impinge on the instrumentation seal table. Once the seal table has failed, the ejected material could come in direct contact with the steel containment liner and subsequently result in a breach of containment. A number of possible mitigation strategies have been postulated to prevent containment failure by this mechanism, among them are depressurization of the primary before vessel failure and lining the containment wall in the seal table area with a refractory material. This analysis postulates the latter option and assumes it is 100% effective in preventing containment failure by direct impingement of the molten core on the containment wall.

The effects of this potential modification were modeled in the SCETs by setting the probability of containment failure by direct impingement (event DI) to zero. Because this modification is completely passive, its effect was reflected in all five SCETs. Further, it is assumed to be 100% reliable. The risk reduction resuting from this improvement is summarized in Table 16.

5.4 Containment Inerting

As for the improved igniter performance, containment inerting is aimed at preventing containment failure by hydrogen burns. However, whereas the igniter system is designed to burn the hydrogen before an explosive mixture can be generated, containment inerting precludes the formation of a combustible mixture by maintaining the containment atmosphere in a de–oxygenated state during normal power operation. Consequently, although the approach is different, the effect of this modification would be virtually identical to the improved igniter performance modification (mod–1) discussed in Section 5.1. Hence, this modification is analyzed identically to what was performed for mod–1 and those results are reproduced in Table 17.

Table 15. Risk comparison between the base case and modification #2 (backup power to the igniters and fans), utilizing the APETs

	50–Mile Population Dose (person–rem per year)	Early Fatalities (per reactor year)	Latent Cancers (per reactor year)
Base Case	10.5	1.89E–5	0.0151
Mod–2 Case	8.7	1.91E–5	0.0117

Table 16. Risk comparison between base case and modification #3 (high pressure melt ejection mitigation, lining the containment wall in the seal table area with refractory material), utilizing SCETs

Plant Damage State Group	50-Mile Population Dose (person-rem per reactor year)		Early Fatalities (per reactor year)		Latent Cancers (per reactor year)	
	Base Case	Mod-3	Base Case	Mod-3	Base Case	Mod-3
SBO-LT PDSG-1	0.487	0.441	2.33E-7	2.33E-7	1.16E-3	1.13E-3
SBO-ST PDSG-2	1.23	1.10	4.22E-7	4.19E-7	3.04E-3	2.93E-3
LOCA PDSG-3	1.07	1.05	2.31E-9	2.26E-9	2.64E-3	2.63E-3
Trans PDSG-5	0.052	0.0516	3.02E-8	3.02E-8	6.23E-5	6.21E-5
ATWS PDSG-6	0.514	0.513	5.49E-7	5.49E-7	6.50E-4	6.5E-4
Totals	3.35	3.16	1.24E-6	1.23E-6	7.55E-3	7.40E-3

Notes: Totals are for the five PDSG for which SCETs have been developed and do not include the two containment bypass sequences (Event-V and SGTR).

Table 17. Risk comparison between base case and modification #4 (inerting containment atmosphere), utilizing SCETs

Plant Damage State Group	50-Mile Population Dose (person-rem per reactor year)		Early Fatalities (per reactor year)		Latent Cancers (per reactor year)	
	Base Case	Mod-4	Base Case	Mod-4	Base Case	Mod-4
SBO-LT PDSG-1	0.487	0.255	2.33E-7	2.50E-9	1.16E-3	5.41E-4
SBO-ST PDSG-2	1.23	0.829	4.22E-7	7.18E-8	3.04E-3	1.95E-3
LOCA PDSG-3	1.07	1.07	2.31E-9	2.31E-9	2.64E-3	2.64E-3
Trans PDSG-5	0.052	0.052	3.02E-8	3.02E-8	6.23E-5	6.23E-5
ATWS PDSG-6	0.514	0.514	5.49E-7	5.49E-7	6.50E-4	6.5E-4
Totals	3.35	2.72	1.24E-6	6.56E-7	7.55E-3	5.85E-3

Notes: Totals are for the five PDSG for which SCETs have been developed and do not include the two containment bypass sequences (Event-V and SGTR).

6. RESULTS AND CONCLUSIONS

Simplified containment event trees have been developed for the Sequoyah Nuclear Power Plant. These trees are based in the vast store of information generated by the Draft NUREG–1150 effort and are simplifications of the accident progression event trees developed and used in those analyses. A virtually perfect comparison was achieved for the SCET containment failure mode results with respect to the APETs. Reasonable agreement was reached between the risk results produced by the SCETs and the APETs. Given further refinement of the source term binner used to generate the 14–character release vector, a more precise reproduction of the APET–predicted risks could no doubt be generated.

Four potential containment modifications were evaluated utilizing either the SCETs or the full APETs. These modifications include: (a) backup power to the hydrogen ignition system, (b) backup power to both igniters and the air recirculation fan system (ARFS), addressed using the APETs, (c) mitigating direct impingement of core material on the containment wall, and (d) preventing hydrogen burns inside containment by inerting the containment atmosphere.

None of the potential containment modifications result in significant risk reduction. However, this is not surprising because the total plant risk for Sequoyah (as calculated by Draft NUREG–1150) is only 12 person–rems per reactor year. A bounding calculation (see Section 5) produces a cost upper limit of $480,000 as being justifiable on plant backfits, assuming 100% of the risk is removed and a 40–year plant life.

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APPENDIX A

ICE CONDENSER DESIGN FEATURES

APPENDIX A

ICE CONDENSER DESIGN FEATURES

Design Feature Comparison

	Cook 1+2	Sequoyah 1+2	McGuire 1+2	Catawba 1+2	Watts Bar 1+2
Utility	Ind./Mich. Power Co.	TVA	Duke	Duke	TVA
Comm. Op.	8/75, 7/78	7/81, 6/82	12/81, 3/84	6/85, 8/86	/92, indef.
Power 100%					
MWe (net)	1020/1060	1148	1129	1129	1177
MWt	3250/3411	3411	3411	3411	3411
Cont. Vol. (ft^3)	1.2M	1.19M	1.196M	1.18M	1.19M
Design pr.	12 psig	12 psig	15 psig	15 psig	15 psig
Est. Fail.		60 psig	84 psig		120psig
Annulus Vol.(ft^3)	N/A	375,000	426,760	484,090	375,000
RWST Vol. (gal.)	350,000	370,000	372,100	350,000	350,000
Cont. Sp.					
# pumps	2	2	2	2	2
Cap. @	3,200 gpm	4,750 gpm	3,400 gpm	[illegible]00 gpm	4,000 gpm
RHR Spray					
# pumps	2	2	2	2	
Cap. @	2,000 gpm	2,000 gpm	1,600 gpm	2,000 gpm	
Service Water Source		Cooling Towers, river	1.8E+8 gal NSW pond	2.7E+8 gal NSW pond	
Fire Prot. System					
# pumps		4	3	3	
Cap. @		1,500 gpm	2,500 gpm	2,500 gpm	

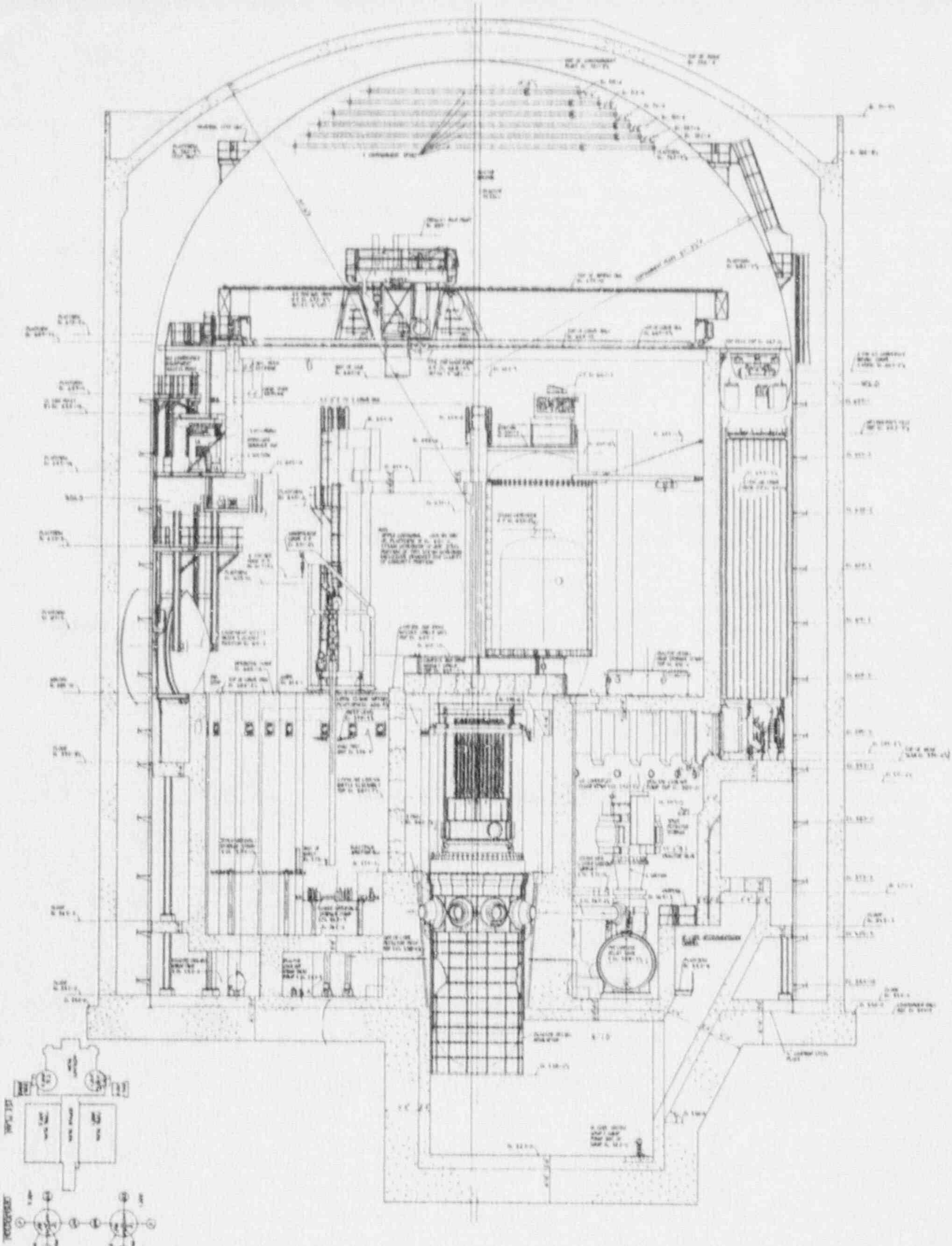

Figure A-1. General Arrangement of Containment - Sideview (from Catawba FSAR figure 1.2.2-15).

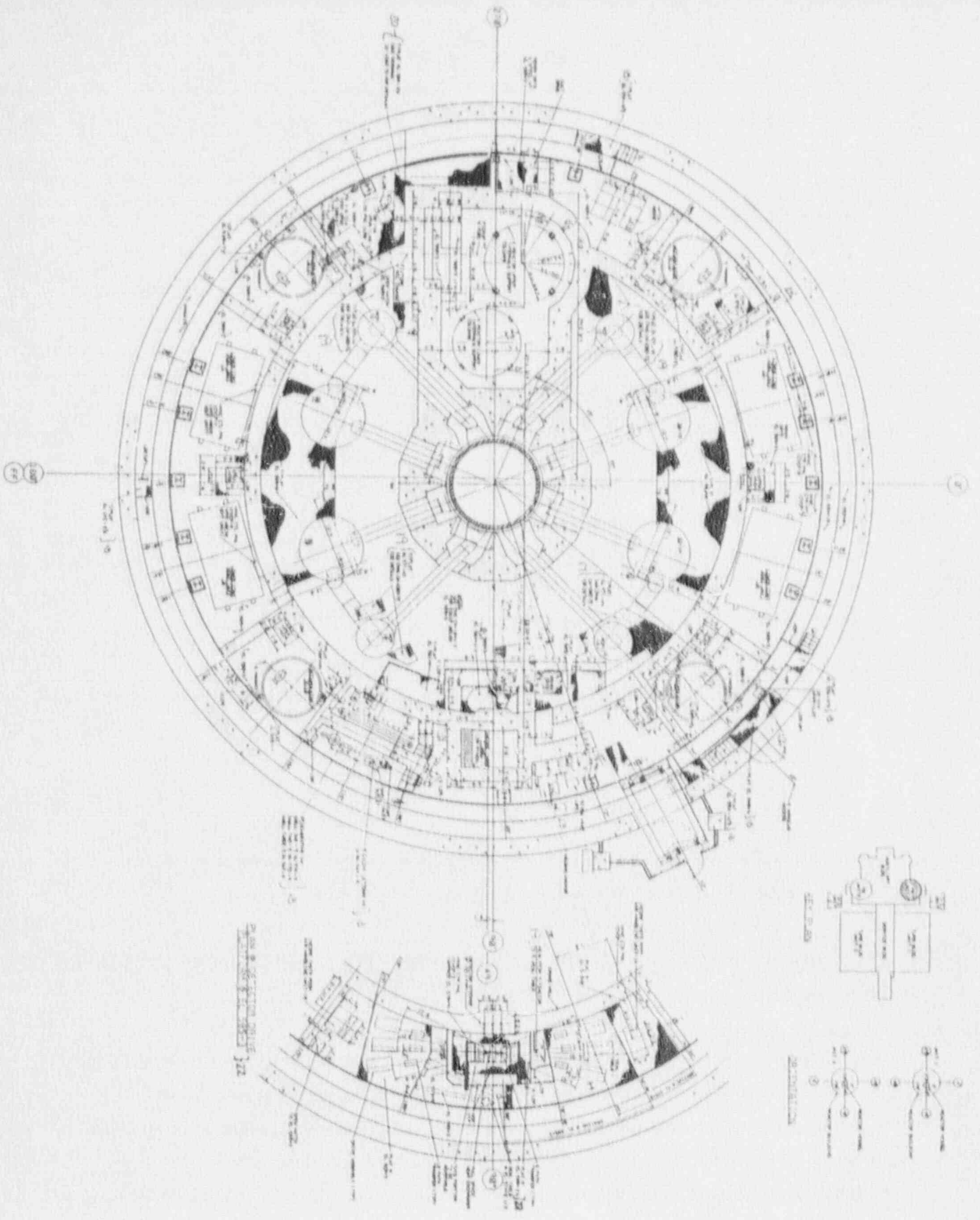

Figure A-2. General Arrangement of Containment - Topview (from Catawba FSAR figure 1.2.2-10).

Hydrogen Mitigation System

McGuire - (from NUREG-0422, McGuire SER supplement 7, May 1983, also see 1984 update of FSAR section 6.2.7).

1) Model 7G glow plug manufactured by General Motors AC Division (1700°F).
2) Powered directly from a 120/14 Vac transformer, each plug has its own transformer.
3) Two redundant group, with five separate circuits and circuit breakers per group, the number of igniters on each circuit ranges from 1 to 10.
4) System is manually actuated from the auxiliary building by switching a total of 14 breakers at six locations in the aux. building (estimated to take 10 min.). System can also be actuated from the main control room and has the means for verifying the system status from there.
5) McGuire site contains two diesel generators per unit with manual cross-ties between units. Also, McGuire has a safe shutdown system with a fifth dedicated diesel generator.
6) HMS consists of 66 igniter assemblies (staff requested two additional igniters in the lower compartment and four additional igniters in the upper compartment).
   - Lower compartment - 20 (10 per train)
   - Ice condenser upper plenum - 12
   - Upper compartment - 8
   - Dead-ended region - 2 in each of eight rooms and 5 pairs in instrument areas.
7) System is surveillance tested quarterly.

Catawba - (Catawba SER, NUREG-0954 Supplement No. 2, June 1984)

The hydrogen mitigation system (HMS) installed at Catawba is identical to that installed at McGuire, except for minor differences in terminal box designation and igniter location.

Sequoyah - Sequoyah SER, NUREG-0011 supplement 6, December 1982 and FSAR Section 6.2.5A.2 Rev.2)

1) Sequoyah uses 120 Vac hermetically sealed thermal igniters manufactured by Tayco Engineering.
2) Tayco igniters exhibit a tendency to cool (to 1500°F) significantly in a spray environment.
3) Igniters are equally divided into two redundant groups, with 16 separate circuits per group, each with an independent circuit breaker and two igniters per circuit. Manual actuation capability for each group is provided in the main control room (one switch per group), along with the status of each group (on-off).
4) The system consists of 68 igniters:

- Lower compartment - 22
- Ice condenser upper plenum - 16
- Upper compartment - 14 (4 around the dome, 4 at intermediate elevations around the S/G enclosures, 4 around the top inside of the crane wall, and one above each of the two air return fans).
- Dead-end regions - 16 (2 in each of eight room).

5) Testing and surveillance will be done to verify that the igniter temperature will be at least 1700°F.

Watts Bar - FSAR Section 6.2.5A, Amendment 55.

1) Watts Bar uses 120 Vac Tayco igniters
2) A total of 68 igniters equally divided into two redundant groups:
   - 22 in the lower compartment inside the crane wall
   - 16 in the upper plenum
   - 16 in dead-ended compartments
   - 4 around the upper compartment dome
   - 4 at intermediate elevations on the outside of the steam generator enclosures
   - 4 around the top inside of the crane wall
   - One above each of the two air return fans.
3) The HMS will be energized manually from the main control room following any accident where conditions indicate inadequate core cooling.

Containment Spray System

Sequoyah - From NUREG/CR-4550, Rev. 1, October 1988, Section 4.6.8.

Both CSS pumps start automatically upon receipt of a Phase-B containment isolation signal from the Engineered Safety Feature Actuation System (ESFAS). The Phase-B isolation signal is initiated by a containment pressure differential of 2.81 psi between the lower compartment and the annulus. A 30-second time delay is included in the CSS pump start circuit.

Sequoyah - From Sequoyah FSAR Section 6.2.3.1.1, page 6.2-97.

"There are no formal design bases established for air cleanup by the Containment Spray System. This was done with the knowledge that water from the Containment Spray System will remove halogens and particulates from the containment atmosphere following a LOCA. No credit, however, was taken for this removal process in accident analyses presented in subsections 15.4.1. In such circumstances, no design bases are needed for this air purification action."

<u>McGuire</u> - From McGuire FSAR Section 6.5.5, page 6.5-9 (1985 Update to FSAR).

Under accident conditions, the Air Return System and the Containment Spray System are activated when the internal pressure in the containment reaches 3 psig. Two out of three hi pressure signals (1 psig) produce an Ss signal or safety injection signal. Two out of four hi-hi pressure signals (3 psig) produce an Sp or containment spray signal.

D. C. Cook - D. C. Cook FSAR, July 1982, page 6.3-2.

"The secondary purpose of the Containment Spray System is the removal of fission products (radioactive iodine isotopes) from the containment atmosphere. The Containment Spray System is designed to deliver sufficient sodium hydroxide solution which, when mixed with water from the Refueling Water Storage Tank which contains approximately 1.5% by weight boric acid (2000 ppm Boron), reactor coolant system water and the melted ice, gives a final spray water pH of approximately 9.3 after the spray additive (NaOH) tank is emptied. The performance of the Containment Spray System for iodine removal with a single Containment Spray Pump operating adequately fulfills the requirements of 10 CFR 100 as described in Chapter 14." NOTE: Cook has sprays in both the upper and lower compartments, the other ice condenser plants have sprays only in the upper compartment.

D. C. Cook - D. C. Cook FSAR, July 1982, page 6.3-6.

The CSS is automatically initiated on receipt of a hi-hi containment spray signal (3.0 psig, 2/4 logic). Similarly, a hi containment pressure signal (1.2 psig, 2/3 logic) initiates a Safety Injection Actuation signal.

Catawba - Catawba FSAR Section 6.2.4.1 page 6.2-50.

Phase A containment isolation is initiated by a hi containment pressure signal (ST). An ST occurs when a containment pressure of 1 psig is sensed by 2/4 containment pressure sensors or upon receipt of a safety injection signal (SS). A phase B containment isolation is initiated by hi-hi containment pressure signal (SP), which occurs when a containment pressure of 3 psig is sensed by the same pressure sensors.

Catawba

"The Containment Spray System is assumed to remove no fission products following a design basis accident and no credit is taken in offsite dose calculations." (Catawba FSAR Section 6.5.2 page 6.5-3.)

The ice condenser design basis includes the removal of iodine from the post LOCA containment atmosphere and thereby reducing the offsite doses following a LOCA. This is accomplished by chemically controlling the ice pH to an alkaline range of 9.0 to 9.5. (Catawba FSAR Section 6.5.4. page 6.5-4, also see the Westinghouse nonproprietary topical report WCAP-7426.)

Watts Bar - Watts Bar FSAR Section 6.2.2-1

Section 6.2.2-1, describes the design bases for the Containment Spray System as primarily containment pressure suppression to "... ensure that the containment pressure cannot exceed the containment shell design pressure of 15.0 psig at 250°F." A secondary design basis is the removal of energy directly from containment after the ice has melted in the ice chest. There is no mention of a radioactivity removal function in the design basis description for the CSS.

APPENDIX B

APET BASED RISK ANALYSIS OF HIS AND ARFS IMPROVEMENT

APPENDIX B
APET BASED RISK ANALYSIS OF HIS AND ARFS IMPROVEMENT

The potential containment improvement of backup power to the Air Return Fan System (ARFS) and Hydrogen Ignition System (HIS) has been evaluated. Unlike the other potential improvements discussed in this report, this fix was examined utilizing the complete APET, as developed by the draft NUREG-1150 effort. The modification was modeled, such that both systems could continue to operate regardless of a loss of all plant power by virtue of a dedicated backup power supply that would be independent of the existing ac power system. With this improvement both fans and igniters would be operable under SBO conditions.

The boundary conditions for this analysis include the assumption that the backup ac power supply would always available. The probability that the operators fail to actuate the HIS when required was retained from the base case APET value of 0.01. The hardware unavailability of the fan system, was also retained from the base case value (0.001). Only the two station blackout PDSs were included in this evaluation because for the other PDS ac power is already available.

B.1. APET Modifications

Only the APETs for PDSs 1 and 2 (SBO-LT and SBO-ST) were modified. The hardware availabilities of the improved ARFS and HIS are assumed to be unchanged from the base APET values of 0.999 and 1.0, respectively. The first APET question that is modified is Question 13, which asks whether the operators actuate the HIS. In the base case, if there is no ac power at the time of uncovering the top of the fuel (UTAF), the igniters will not be actuated. For the improvement analysis, it was assumed that a backup source of ac power was always available and that the unavailability of the igniters, caused by operators failing to actuate them, remained at the base case value of 0.01.

The next question to be modified is Question 14, which addresses the status of the ARFS at UTAF. In the base case, because ac power is unavailability for the SBO PDSG, the air return fans are not operating at UTAF. The probability that the fans can operate if power is recovered during core degradation is 0.999. The probability that the fans have failed and cannot operate upon demand is 0.001 (hardware unavailability of the fans system). For the improvement analysis, it was assumed that a backup source of ac power was always available and that the unavailability of the fans remained at the base case value. Therefore, in the improved case, with ac power available to the ARF system, the availability of the fans at UTAF is 0.999.

The next APET question to be modified was Question 28, which asks whether the fans are operational in the early time period (between core uncovering and VB). In the base case, there are four possible cases. First, if the fans were operating at UTAF, then they continue to operate. (This case was not applicable for SBO.) Next, if the fans were failed at the start of the accident then they remained failed. Third, if the fans were available to operate at the start of the accident, and ac power was recovered, then the fans now operate. Finally, if the fans were available to operate at the start of the accident, and ac power was not recovered, then the fans remain available to operate when power is restored. In the improvement analysis, with backup ac power available to supply the ARF system, the last two cases described above are no longer applicable and were removed from the APET.

Question 31 asks whether the air return fans are effective in mixing the containment atmosphere before hydrogen ignition occurs. For the base case, three cases are possible. First, if the fans are initially operating, then the fans are effective and the hydrogen is uniformly distributed throughout the containment. Second if the fans are available to operate and ac power is recovered in the early period of a station blackout, the probability of the ARF to mix the containment atmosphere prior to hydrogen ignition was 0.830. Finally, for cases without ac power recovery or in which the fans have failed, the fans will be ineffective. For the improvement analysis, the second case is no longer applicable and was removed. Also, the sampling file was modified to eliminate the sampling of Case 2.

Question 47 asks whether the hydrogen igniters are operating during core degradation and addresses accidents involved with loss of offsite power and subsequent power recovery. However, in the improvement analysis, an ac power supply to the igniters is always available. Therefore, this question was modified to eliminate those cases involving ac power recovery which are no longer applicable.

Question 49 addresses whether hydrogen ignition occurs in the ice condenser during core degradation (CD). Case 2 of this question was modified to eliminate those sequences involving fan recovery that were no longer valid for the improved case.

Question 50 and 51 address whether hydrogen ignition occurs during CD in the upper plenum and upper compartment, respectively. Case 3 of both questions was modified to eliminate those sequences involving fan recovery that were no longer valid for the improved case.

Question 92 asks if the fans are operating late. Case 3 was eliminated since it involved only sequences in which the fans operate after ac power is recovered. In the improved case backup power to the fans is always available.

The final question modified was Question 100. This question asked if the igniters were operating late. Cases 2 and 3 were eliminated. Both of these cases involved station blackout sequences with ac power recovery after VB. For the improved case with backup power supply to the igniters, these two case are no longer valid.

B.2. Accident Progression Findings

Table B-1 shows the effects of the backup power supply to the fans and igniters on the conditional probabilities of the accident progression bins for the two SBO PDSs.

Table B-1. Conditional probability of accident progression bins at Sequoyah, with backup power to fans and igniters.

		Conditional Probabilities	
Accident Progression Bin	Case	PDS-1 (SBO-LT)	PDS-2 (SBO-ST)
CF[a] before VB,[b] early CF	Sensitivity:	1.16E-03	2.30E-03
	Base case:	1.25E-02	1.50E-02
VB, alpha, early CF	Sensitivity:	7.09E-04	2.55E-03
	Base case:	6.87E-04	2.51E-03
VB, RCS[c] pressure > 200 psi, early CF	Sensitivity:	4.60E-02	4.64E-02
	Base case:	5.55E-02	6.57E-02
VB, RCS pressure < 200 psi, early CF	Sensitivity:	1.93E-02	2.98E-02
	Base case:	3.24E-02	6.53E-02
VB, H_2 burn, late CF	Sensitivity:	5.84E-04	1.66E-03
	Base case:	9.60E-02	1.76E-01
VB, BMT[d] or very late OP[e]	Sensitivity:	8.16E-02	1.42E-01
	Base case:	4.53E-02	7.69E-02
Bypass	Sensitivity:	1.43E-04	1.86E-03
	Base case:	1.32E-04	1.74E-03
VB, no CF	Sensitivity:	2.53E-01	4.05E-01
	Base case:	1.58E-01	2.27E-01
No VB, early or no CF	Sensitivity:	5.73E-01	3.48E-01
	Base case:	5.71E-01	3.46E-01

a. Containment Vessel.
b. Vessel Breach.
c. Reactor Coolant System.
d. Basemat melt-through.
e. Overpressurization.

The effects of this potential modification on the accident progression bins are as follows. For both PDS-1 and PDS-2, given vessel breach, the probability of early containment failure (ECF) decreased 34% and 45%, respectively, from the base case values. For PDS-1, the percentage of sequences resulting in ECF is 6.7% versus 10.1% for the base case. For PDS-2, 8.1% of the sequences resulted in ECF versus 14.9% for the base case. The conditional probabilities were decreased for each of the four APBs that contribute to ECF with the exception of the alpha mode failure bin which increased 3.2% and 1.6%, for PDS-1 and PDS-2, respectively. These small increases are due to the increased number of sequences that do not fail containment prior to vessel breach.

The probability of late containment failure from late hydrogen burns was decreased more than two orders of magnitude. For PDSs 1 and 2, the conditional probabilities were reduced by factors of 164 and 106, respectively. These substantial decreases are the result of the combined effects of the fans and igniters operating throughout the accident. The conditional probabilities of basemat meltthrough (BMT) or very late overpressurization (OP) from a build up of steam and noncondensibles increased 80% and 85% from base case values of 4.53E-02 and 7.69E-02, for PDSs 1 and 2, respectively. Of the two very late failure modes (BMT and OP), BMT is the more prevalent failure mode by at least an order of magnitude. For example, in the base case analysis, the conditional probabilities of BMT and OP, for PDSs 1 and 2, are 4.4E-02 and 4.0E-03, and 7.87E-02 and 1.7E-03, respectively. In the sensitivity analysis, the conditional probability of both failure modes increased because the early failures are averted and more scenarios reach the point where late failures are possible.

The conditional probabilities of bypass reported in Table B-1 show increases of 8% and 7% above the base case values of 1.32E-04 and 1.74E-03, for PDSs 1 and 2, respectively. However, these increases are artifacts of truncating paths through the accident progression event tree when the path frequency is less than 1.0E-05. In fact, the only failure mode contributing to the bypass bin for the station blackout PDSs is temperature induced steam generator tube ruptures (SGTR) which are not affected by the addition of backup power supply to the fans and igniters. The conditional probability of a temperature induced SGTR reported in the "Branch and Case Frequency" table listed in the EVNTRE output is 1.78E-04 and 2.14E-03, for PDSs 1 and 2, respectively. These probabilities remained unchanged in the sensitivity analysis. However, due to the tree modifications in the sensitivity analysis, different paths frequencies developed, so that different paths were truncated than for the base case tree. These differences in the truncated paths resulted in different probabilities of bypass for the base case and sensitivity case.

The probability of vessel breach with no containment failure increased 60% and 78% above the base case values of 1.58E-01 and 2.27E-01, for PDSs 1 and 2, respectively. These increases in no containment failures are due to the fans and igniters eliminating failures from early and late hydrogen burns. The probability of no vessel breach remains unchanged within the uncertainty of the analysis.

Table B-2 presents the accident progression bin probabilities weighted over the two station blackout PDSs, for the base and sensitivity cases. The results are similar to those discussed above for the individual PDSs. With the addition of backup power to the fans and igniters, early containment failures are seen to decrease by 42% from a base case value of 1.33E-01. Alpha mode failures increase by 1.6%. Late failures caused by hydrogen burns decreased by a factor of 115 and very late failures from BMT or late overpressurizations increased 83%. Bypass failures increased 6.6%. Again this increase in bypass failures is an artifice of the event tree truncations. The probability of no containment failure increased 74% and the probability of no vessel breach remained unchanged.

Table B-2. Comparison of station blackout weighted averages of the accident progression bin probabilities for Sequoyah, with backup power for fans and igniters.

	SBO Weighted Average Conditional Probabilities	
Accident Progression Bin	Base	Sensitivity
CF[a] before VB,[b] early CF	1.42E-02	1.92E-03
VB, alpha, early CF	1.91E-03	1.94E-03
VB, RCS[c] > 200 psi, early CF	6.23E-02	4.62E-02
VB, RCS < 200 psi, early CF	5.44E-02	2.64E-02
VB, H_2 burn, late CF	1.49E-01	1.30E-03
VB, BMT[d] or very late OP[e]	6.65E-02	1.22E-01
Bypass	1.21E-03	1.29E-03
VB, no CF	2.04E-01	3.55E-01
No VB, early or no CF	4.21E-01	4.22E-01

a. Containment Failure.
b. Vessel Breach.
c. Reactor Coolant System.
d. Basemat melt-through.
e. Overpressurization.

Table B-3 presents the accident progression bin probabilities weighted over all PDSs for the base and sensitivity cases. Because, the backup power supply to the fans and igniters only affected the two station blackout PDSs, the effect of the sensitivity is diminished when weighted over all PDSs. However, the overall trends remain: early containment failures are decreased by 21%, late failures are decreased by a factor of 35, very late failures from BMT and overpressurization are increased 7.5%, and no containment failures are increased 14%.

Table B-3. Comparison of weighted average accident progression bin probabilities for Sequoyah with backup power for fans and igniters.

	Weighted Average Conditional Probabilities	
Accident Progression Bin	Base: All PDSGs	Sensitivity: All PDSGs
CF[a] before VB,[b] early CF	5.11E-03	2.08E-03
VB, alpha, early CF	1.69E-03	1.69E-03
VB, RCS[c] > 200 psi, early CF	3.61E-02	3.21E-02
VB, RCS < 200 psi, early CF	2.29E-02	1.59E-02
VB, H_2 burn, late CF	3.78E-02	1.09E-03
VB, BMT[d] or very late OP[e]	1.87E-01	2.01E-01
Bypass	4.82E-02	4.82E-02
VB, no CF	2.63E-01	3.01E-01
No VB, early or no CF	3.76E-01	3.77E-01

a. Containment Vessel.
b. Vessel Breach.
c. Reactor Coolant System.
d. Basemat melt-through.
e. Overpressurization.

B.3. Risk Results

As was done in the base case benchmarking analysis, two methods were used to estimate the affects of the potential modification on risk. The first method used the PARTITION code to estimate the mean risk potentials in terms of early and latent fatalities. The second is the more detailed and precise method of using the conditional consequences calculated by the MACCS code. The mean risk potential estimates for both this sensitivity case and the base case are given in Table B-4. The mean risk measures calculated using the MACCS consequences are shown in Table B-5.

The effect of this potential improvement on the mean risk potentials, presented in Table B-4, is an 18% and 19% reduction in the mean early and latent fatality potentials, respectively. The effect on the mean risk estimates (shown on Table B-5) is a 17% to 22% reduction in all of the risk estimates, with the exception of early fatalities, which increased slightly by 1%. This latter result is somewhat surprising since the mean risk potential for early fatalities decreased nearly 18%.

Table B-4. Sequoyah mean risk potentials: comparison of base case with the backup power supply to fans and igniters sensitivity case.

	Mean Early Fatalities (per year)	Mean Latent Fatalities (per year)
Base Case	8.25E-05	1.13E-01
Sensitivity	6.77E-05	9.19E-02
Reduction	17.9%	18.7%

Table B-5. Sequoyah mean risk measures: comparison of base case with the backup power supply to fans and igniters sensitivity case.

	Mean Early Fatalities (per year)	Mean Latent Fatalities (per year)	Mean Dose 50-Mile (Person-Rem per year)	Mean Dose 1000-Mile (Person-Rem per year)
Base Case	1.89E-05	1.51E-02	1.05E+01	8.93E+01
Sensitivity	1.91E-05	1.17E-02	8.69E+00	6.90E+01
Reduction[a]	-1.1%	22.5%	17.2%	22.7%

a. A negative value indicates an increase in the risk measure.

APPENDIX C

DATA FILE LISTINGS FOR SEQUOYAH SCET DEVELOPMENT

APPENDIX C
DATA FILE LISTINGS FOR SEQUOYAH SCET DEVELOPMENT

The listings provided in this appendix are of two types. The first set (four listings) consists of the EVNTRE binning data used to extract simplified containment event trees (SCETS) from the accident progression event trees (APETs) used in the NUREG-1150 analysis of Sequoyah. The question references in this set refer to APET questions documented in the NUREG/CR-4551 volume for Sequoyah. The second set (also four listings) consists of the PSTEVNT input used to reduce the SCET endstates to an approximation of the NUREG-1150 accident progression bins. The question references in this set refer to SCET events, or questions, as defined in the comments of the first four listings.

LISTING 1

```
Sequoyah SCET Binning -- PDSG-1, Slow SB
 16          '1'        '2'        '3'        '4'        '5'
             '6'        '7'        '8'        '9'       '10'
            '11'       '12'       '13'       '14'       '15'
            '16'
  2   2     NoB-L       B-L             $ 1. Initial containment leak or
  1   1       12                        $    isolation failure.
               2
            NoB-Leak
  1   2       12
               1
            B-Leak
  2   2      NoB1        B1             $ 2. Failure to restore AC power early.
  1   1       22
               1
            E-ACP
  2   2       22         22
               2        + 3
            EaACP      EfACP
  2   2     NoCF1       CF1             $ 3. Cont. fails pre-VB (H2 burn).
  1   1       58
               1
             EnCF
  1   2       58
              /1
             EnCF
  2   2      NoE-IBP  E-IBP             $ 4. Large ice bypass prior to VB.
  2   1       59         59
               3        + 2
             E2nIBP   E2-IBP2
```

```
1   2          59
                1
          E2-IBP1
2   2        NoDP         DP              $ 5. Failure to depressurize the reactor.
1   1          25
                4
          I-LoPr
1   2          25
               /4
          I-LoPr
2   2        NoVB         VB              $ 6. RPV fails (vessel breach).
1   1          26
                1
          noVB
1   2          26
                2
               VB
2   2      NoIVSE       IVSE              $ 7. In-vessel steam explosion
1   1          64                         $    fails the vessel and containment.
                2
       NoAlpha
1   2          64
                1
         Alpha
2   2      NoEVSE       EVSE              $ 8. Ex-vessel steam explosion at VB
2   1          71         71
                1        + 3
           EVSE     noEVSE
1   2          71
                2
       EVSE-CF
2   2      NoOPVB       OPVB              $ 9. OP fails cont. at VB
4   1          64         70          71         82
               /2       + /3        +  2       +  1
       NoAlpha       NoRkt     EVSE-CF       InCF
4   2          64         70          71         82
                2        * 3        * /2       * /1
       NoAlpha       NoRkt     EVSE-CF       InCF
2   2        NoDI         DI               $ 10. Direct impingement on the
1   1          78                          $     seal table wall (and hence
                2                          $     containment failure)
     InCDFImp
1   2          78
                1
     I-CFDImp
2   2    NoI2-IBP     I2-IBP               $ 11. Large ice bypass after VB.
2   1          83         83
                3        + 2
        I2nIBP    I2-IBP2
1   2          83
                1
      I2-IBP1
2   2       NoCCI        CCI               $ 12. Prompt CCI occurs.
2   1          89         89
                4        + 5
```

```
              SDlyCCI   noI2CCI
   3    2          89        89        89
                    1       + 2       + 3
               DryCCI   SScrCCI   DScrCCI
   2    2        NoB2        B2                  $ 13. Failure to restore AC power late
   1    1          90
                    1
                L-ACP
   1    2          90
                   /1
                L-ACP
   2    2       NoOPL       OPL                  $ 14. Late over-pressure (H2 or slow OP)
   1    1         103
                    1
                 LnCF
   1    2         103
                   /1
                 LnCF
   2    2        NoB3        B3                  $ 15. Failure to restore AC power very
late
   1    1         105
                    1
               L2-ACP
   1    2         105
                   /1
               L2-ACP
   2    2      NoVLCF      VLCF                  $ 16. Very late failure  (OP or BMT)
   2    1         107       109
                    2       * 1
                 noMT     L2nCF
   2    2         107       109
                    1      + /1
                  BMT     L2nCF
   1
  16        1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
  SORT ALL BINS ==>
```

LISTING 2

```
Sequoyah SCET Binni~g -- PDSG-3, LOCA
 13           '1'       '2'       '3'       '4'       '5'
              '6'       '7'       '8'       '9'       '10'
              '11'      '12'      '13'
  2   2       CI        NCI                 $ 1. Containment isolation failure
  1   1       12
               2
        noB-Leak
  1   2       12
               1
          B-Leak
  2   2     NoECF       ECF                 $ 2. Cont. fails pre-VB (H2 burn).
  5   1       48        49        50        51        58
             (/1       * /1      * /1      * /1)    +  1
                                                   EnCF
  5   2       48        49        50        51        58
             (1        + 1       + 1       + 1)    *  /1
                                                   EnCF
  2   2       LP        HP                  $ 3. Failure to depressurize the reactor.
  1   1       25
               4
          I-LoPr
  1   2       25
              /4
          I-LoPr
  2   2     NoVB        VB                  $ 4. RPV fails (vessel breach).
  1   1       26
               1
            noVB
  1   2       26
               2
              VB
  2   2   NoE-HR      E-HR                  $ 5. Early containment heat
  4   1       27  28   29  30               $    removal failure.
               1 * 1 * /1 * 3
          E-Sp E-Fan E-Mlt1  EnIBP
  4   2       27   28  29   30
              /1 + /1 + 1 + /3
          E-SP E-Fan  E-Mlt1  EnIBP
  2   2   NoIVSE      IVSE                  $ 6. In-vessel steam explosion
  2   1       64        70                  $    fails the vessel and containment.
               2      * /1
         NoAlpha    Rkt-CF
  2   2       64        70
               1      + 1
           Alpha    Rkt-CF
  2   2   NoEVSE      EVSE                  $ 7. Ex-vessel steam explosion at VB
  2   1       71        71
               1      + 3
            EVSE    noEVSE
  1   2       71
               2
```

```
            EVSE-CF
 2    2      NoCFVB      CfVB              $ 8. OP fails cont. at VB
 4    1          58        64        71       82
                 /1      + /2       + 2      + 1
               EnCF   NoAlpha   EVSE-CF     InCF
 4    2          58        64        71       82
                  1       * 2      * /2     * /1
               EnCF   NoAlpha   EVSE-CF     InCF
 2    2        NoDI        DI              $ 9. Direct impingement on the
 1    1          78                        $    seal table wall (and hence
                  2                        $    containment failure)
          InCDFImp
 1    2          78
                  1
          I-CFDImp
 2    2       NoDNC       DNC              $ 10. Coolable debris bed not formed
 1    1          88
                  1
              I-CDB
 1    2          88
                  2
              InCDB
 2    2      NoL-HR      L-HR     $ 11. Late and V late cont. heat removal failure
 3    1          91        92       106
                  1       * 1       * 1
               L-Sp     L-Fan     L2-Sp
 3    2          91        92       106
                 /1      + /1      + /1
               L-Sp     L-Fan     L2-Sp
 2    2       NoLCF       LCF              $ 12. Late over-pressure (H2 or slow OP)
 1    1         103
                  1
               LnCF
 1    2         103
                 /1
               LnCF
 2    2      NoVLCF      VLCF              $ 13. Very late failure  (OP or BMT)
 2    1         107       109
                  2       * 1
               noMT     L2nCF
 2    2         107       109
                  1      + /1
                BMT     L2nCF
 1
13      1 2 3 4 5 6 7 8 9 10 11  12 13
SORT ALL BINS ==>
```

LISTING 3

```
Sequoyah SCET Binning -- PDSG-5, Transient
 10            '1'        '2'        '3'        '4'        '5'
               '6'        '7'        '8'        '9'       '10'
  2   2        CI         NCI              $ 1. No containment isolation.
  1   1        12
                2
         noB-Leak
  1   2        12
                1
           B-Leak
  2   2    NoSGTR        SGTR              $ 2. Temperature induced SGTR.
  1   1        20
                2
         noE-SGTR
  1   2        20
                1
           E-SGTR
  2   2        HP          LP              $ 3. PCS fails before VB.
  1   1        25                          $     (low pressure)
               /4
           InLoPr
  1   2        25
                4
           I-LoPr
  2   2      NoVB          VB              $ 4. RPV fails (vessel breach).
  1   1        26
                1
             noVB
  1   2        26
                2
               VB
  2   2    NoEVSE        EVSE               $ 5. Ex-vessel steam explosion at VB
  2   1        71          71
                1         + 3
             EVSE      noEVSE
  1   2        71
                2
          EVSE-CF
  2   2    NoOPVB        OPVB               $ 6. OP fails cont. at VB
  3   1        58          71          82
               /1       +   2       +   1
             EnCF     EVSE-CF        InCF
  3   2        58          71          82
                1        * /2        * /1
             EnCF     EVSE-CF        InCF
  2   2      NoDI          DI               $ 7.  Direct impingement on the
  1   1        78                           $     seal table wall (and hence
                2                           $     containment failure)
        InCDFImp
  1   2        78
                1
         I-CFDImp
```

```
  2   2     NoDNC        DNC              $ 8.  Coolable debris bed not formed
  1   1        88
                1
            I-CDB
  1   2        88
                2
            InCDB
  2   2    NoL-HR       L-HR             $ 9. Late and V late cont. heat removal
failure
  3   1        91         92     106     $     (4 to 6 hours)
                1        * 1     * 1
             L-Sp      L-Fan   L2-Sp
  3   2        91         92     106
               /1       + /1    + /1
             L-Sp      L-Fan   L2-Sp
  2   2    NoVLCF       VLCF             $ 10. Very late failure  (OP or BMT)
  2   1       107        109
                2        * 1
             noMT      L2nCF
  2   2       107        109
                1       + /1
              BMT      L2nCF
  1
 10      1 2 3 4 5 6 7 8 9 10
SORT ALL BINS ==>
```

LISTING 4

```
Sequoyah SCET Binning -- PDSG-6, ATWS
 13           '1'        '2'        '3'        '4'        '5'
              '6'        '7'        '8'        '9'       '10'
             '11'       '12'       '13'
  2    2    NoSGTR      SGTR                 $ 1. SGTR occurs before VB
  1    1         1
                /5
            B-SGTR
  1    2         1
                 5
            B-SGTR
  2    2      NoCI        CI                 $ 2. Containment isolation failure
  1    1        12
                 2
         noB-Leak
  1    2        12
                 1
            B-Leak
  2    2     NoCF1       CF1                 $ 3. Cont. fails pre-VB (H2 burn).
  5    1        48        49         50         51         58
               (/1      * /1       * /1       * /1)    +   1
                                                         EnCF
  5    2        48        49         50         51         58
                (1       + 1        + 1        + 1)    *  /1
                                                         EnCF
  2    2        LP        HP                 $ 4. Failure to depressurize the reactor.
  1    1        25
                 4
            I-LoPr
  1    2        25
                /4
            I-LoPr
  2    2      NoVB        VB                 $ 5. RPV fails (vessel breach).
  1    1        26
                 1
              noVB
  1    2        26
                 2
                VB
  2    2    NoIVSE      IVSE                 $ 6. In-vessel steam explosion
  2    1        64        70                 $    fails the vessel and containment.
                 2      * /1
           NoAlpha    Rkt-CF
  2    2        64        70
                 1       + 1
             Alpha    Rkt-CF
  2    2    NoEVSE      EVSE                 $ 7. Ex-vessel steam explosion at VB
  2    1        71        71
                 1       + 3
              EVSE    noEVSE
  1    2        71
                 2
```

```
            EVSE-CF
  2    2     NoOPVB       OPVB               $ 8. OP fails cont. at VB
  4    1         58         64        71          82
                 /1       + /2      +  2        +  1
               EnCF    NoAlpha   EVSE-CF        InCF
  4    2         58         64        71          82
                  1       * 2       * /2        * /1
               EnCF    NoAlpha   EVSE-CF        InCF
  2    2       NoDI         DI               $ 9. Direct impingement on the
  1    1         78                          $    seal table wall (and hence
                  2                          $    containment failure)
           InCDFImp
  1    2         78
                  1
           I-CFDImp
  2    2       NoCD         CD               $ 10. Coolable debris bed not formed
  1    1         88
                  1
              I-CDB
  1    2         88
                  2
              InCDB
  2    2     NoL-HR       L-HR               $ 11. Late and V late cont. heat removal
failure
  3    1         91         92       106     $      (4 to 6 hours)
                  1        * 1       * 1
               L-Sp      L-Fan     L2-Sp
  3    2         91         92       106
                 /1       + /1      + /1
               L-Sp      L-Fan     L2-Sp
  2    2      NoOPL        OPL               $ 12. Late over-pressure (H2 or slow OP)
  1    1        103
                  1
               LnCF
  1    2        103
                 /1
               LnCF
  2    2     NoVLCF       VLCF               $ 13. Very late failure  (OP or BMT)
  2    1        107        109
                  2        * 1
               noMT      L2nCF
  2    2        107        109
                  1       + /1
                BMT      L2nCF
  1
 13     1 2 3 4 5 6 7 8 9 10 11 12 13
 SORT ALL BINS ==>
```

LISTING 5

```
Sequoyah Source Term Rebinning - PDSG-1 and 2, SBO
14      CF-Time       Sprays        CCI      RCS-Pres    VB-Mode      SGTR
        Amt-CCI       Zr-Ox         HPME     CF-Size     RCS-Hole     E2-IC
          I2-IC       ARFans
 7   7  V-Dry         V-Wet     CF-Early   CF-atVB     CF-Late     CF-VLate
           NoCF
 2   1        1   1               $ A.  Event V, not scrubbed
              1 * /1
          V-Dry
 2   2        1   1               $ B.  Event V, scrubbed
              1 * /1
          V-Wet
 2   3        1   3               $ C.  CF during core degradation
              2 + 2
        CF-Early
 4   4        7   8   9   10      $ D.  CF at vessel breach
              2 + 2 + 2 + 2
        CF-atVB
 1   5       14                   $ E.  Late CF
              2
        CF-Late
 1   6       16                   $ F.  Very late CF
              2
        CF-VLate
 8   7        1   3   7   8   9  10  14  16   $ G. No containment failure
              1 * 1 * 1 * 1 * 1 * 1 * 1 * 1
           NoCF
 8   8  Sp-Early     Sp-E+I     Sp-E+I+L    SpAlways    Sp-Late     Sp-L+VL
          Sp-VL      Sp-NonOp
 3   1        2  13  15           $ A.  Sprays operate only early
              1 * 2 * 2
        Sp-Early
 2   2        1   1               $ B.  Early and intermediate
              1 * /1
          Sp-E+I
 3   3        2  13  15           $ C.  Early and late, not very late
              1 * 1 * 2
        Sp-E+I+L
 3   4        2  13  15           $ D.  At all times
              1 * 1 * 1
        SpAlways
 3   5        2  13  15           $ E.  Late only
              2 * 1 * 2
        Sp-Late
 3   6        2  13  15           $ F.  Late and very late
              2 * 1 * 1
        Sp-L+VL
 3   7        2  13  15           $ G.  Very late only
              2 * 2 * 1
          Sp-VL
 3   8        2  13  15           $ H.  Never
              2 * 2 * 2
```

```
         Sp-Never or Sp-Final
6    6   Prmt-Dry     Prmt-Shl      No-CCI     Prmt-Dp      SDly-Dry    LDly-Dry
4    1          2   5   6  12              $ A.  CCI is dry and starts immediately
                2 * 2 * 2 * 2
         Prmt-Dry
4    2          2    5   6  12             $ B.  CCI occurs under 5 ft of water
                2 *  1 * 2 * 2
         Prmt-Shl
3    3          6    6  12                 $ C.  CCI does not occur
                1 +(2 * 1)
          No-CCI
2    4               6  12                 $ D.  CCI occurs under 10 ft of water
                     2 * 2
         Prmt-Dp
2    5          1    1                     $ E.  CCI occurs after a delay,
                1 * /1                     $     cooling water not replenished
         SDly-Dry
2    6          1    1                     $ F.  CCI occurs after a long delay
                1 * /1
         LDly-Dry
4    4      SSPr         HiPr         ImPr         LoPr
2    1          1    1                     $ A.  System setpoint pressure (2500)
                1 * /1
            SSPr
1    2          5                          $ B.  1000-2000 psia
                2
            HiPr
2    3          1    1                     $ C.  200-1000 psia
                1 * /1
            ImPr
1    4          5                          $ D.  < 200 psia
                1
            LoPr
6    6   VB-HPME      VB-Pour      VB-BtmHd       Alpha       Rocket        No-VB
3    1          5   6   7                  $ A.  HPME and DCH
                2 * 2 * 1
         VB-HPME
3    2          5   6   7                  $ B.  Molten pour at low pressure
                1 * 2 * 1
         VB-Pour
2    3          1    1                     $ C.  Gross failure of bottom head
                1 * /1
         VB-BtmHd
2    4          6   7                      $ D.  Alpha mode failure
                2 * 2
           Alpha
2    5          1    1                     $ E.  Upward acceleration of vessel
                1 * /1
          Rocket
1    6          6                          $ F.  No vessel breach
                1
           No-VB
3    3      SGTR       SG-SRVO      No-SGTR
2    1          1    1                     $ A.  SGTR occurs, secondary RVs reclose
                1 * /1
```

```
        SGTR
2   2       1   1             $ B.  SGTR, secondary RVs stuck open
            1 * /1
      SG-SRVO
2   3       1   1             $ C.  SGTR does not occur
            1 + /1
      No-SGTR
4   4   Hi-CCI     Med-CCI     Lo-CCI     No-CCI
1   1      12                 $ A.  CCI involves 70-100%
            2
       Hi-CCI
2   2       1   1             $ B.  CCI involves 30-70%
            1 * /1
      Med-CCI
2   3       1   1             $ C.  CCI involves 0-30%
            1 * /1
       Lo-CCI
1   4      12                 $ D.  No CCI occurs
            1
       No-CCI
2   2  Lo-ZrOx     Hi-ZrOx
1   1       5                 $ A.  0-40% of core Zr was oxidized
            1
      Lo-ZrOx
1   2       5                 $ B.  > 40% of core Zr was oxidized
            2
      Hi-ZrOx
4   4  Hi-HPME     Md-HPME     Lo-HPME     No-HPME
3   1       5   6   7         $ A.  Pct core ejected > 40%
            2 * 2 * 1
      Hi-HPME
2   2       1   1             $ B.  Pct core ejected 20-40%
            1 * /1
      Md-HPME
2   3       1   1             $ C.  Pct core ejected < 20%
            1 * /1
      Lo-HPME
3   4       5   6   7         $ D.  No HPME
            1 + 1 + 2
      No-HPME
4   4  Cat-Rpt     Rupture       Leak      No-CF
3   1       3           9   14  $ A.  Gross structural failure
            2 +         2 + 2
      Cat-Rpt
2   2       7   8             $ B.  Hole > 7 ft2
            2 + 2
      Rupture
3   3      10   1  16         $ C.  Hole is about 0.1 ft2
            2 + 2 + 2
         Leak  or    BMT
8   4       1   3   7   8   9  10  14  16  $ D.  No containment failure
            1 * 1 * 1 * 1 * 1 * 1 * 1 * 1
       Bypass  or   No-CF
2   2   1-Hole     2-Holes
1   1       7                 $ A.  One hole - no natural circ.
```

```
            1
        1-Hole
 1   2      7                     $ B.  Two holes - natural circulation
            2
        2-Holes
 3   3  E2-InByP     E2-IpByP     E2-IByP
 1   1      4                     $ A.  No ice condenser bypass
            1
        E2-InByP
 2   2      1    1                $ B.  10% ice bypass
            1 * /1
        E2-IpByP
 1   3      4                     $ C.  Total ice bypass
            2
        E2-IByP
 3   3  I2-InByP     I2-IpByP     I2-IByP
 1   1     11                     $ A.  No ice condenser bypass
            1
        I2-InByP
 2   2      1    1                $ B.  10% ice bypass
            1 * /1
        I2-IpByP
 1   3     11                     $ C.  Total ice bypass (or melted)
            2
        I2-IByP
 4   4  ARF-Erly    ARF-E+L     ARF-Late     No-ARF
 2   1       2   13               $ A.  Air return fans early only
             1 *  2
        ARF-Erly
 2   2       2   13               $ B.                    early and late
             1 *  1
        ARF-E+L
 2   3       2   13               $ C.                    late only
             2 *  1
        ARF-Late
 2   4       2  13                $ D.  No air return fans
             2 * 2
         No-ARF
```

LISTING 6

```
Sequoyah Source Term Binning -- PDSG-3, LOCA
 14       CF-Time       Sprays        CCI      RCS-Pres     VB-Mode       SGTR
          Amt-CCI       Zr-Ox         HPME     CF-Size      RCS-Hole      E2-IC
            I2-IC       ARFans
  7   7   V-Dry         V-Wet       CF-Early   CF-atVB      CF-Late       CF-VLate
           NoCF
  2   1         1   1                     $ A.  Event V, not scrubbed
                1 * /1
          V-Dry
  2   2         1   1                     $ B.  Event V, scrubbed
                1 * /1
          V-Wet
  2   3         1   2                     $ C.  CF during core degradation
                2 +  2
        CF-Early
  4   4         6   7   8   9             $ D.  CF at vessel breach
                2 + 2 + 2 + 2
        CF-atVB
  1   5        12                         $ E.  Late CF
                2
        CF-Late
  1   6        13                         $ F.  Very late CF
                2
        CF-V!ate
  8   7         1   2   6   7   8   9  12  13  $ G.  No containment failure
                1 * 1 * 1 * 1 * 1 * 1 * 1 * 1
           NoCF
  8   8   Sp-Early     Sp-E+I     Sp-E+I+L    SpAlways    Sp-Late     Sp-L+VL
            Sp-VL      Sp-NonOp
  2   1         5  11                     $ A.  Sprays operate only early
                1 *  2
        Sp-Early
  2   2         1   1                     $ B.  Early and intermediate
                1 * /1
          Sp-E+I
  2   3         1   1                     $ C.  Early and late, not very late
                1 * /1
        Sp-E+I+L
  2   4         5  11                     $ D.  At all times
                1 *  1
        SpAlways
  2   5         1   1                     $ E.  Late only
                1 * /1
        Sp-Late
  2   6         5  11                     $ F.  Late and very late
                2 *  1
        Sp-L+VL
  2   7         1   1                     $ G.  Very late only
                1 * /1
           Sp-VL
  2   8         5  11                     $ H.  Never
                2 *  2
```

```
          Sp-Never or Sp-Final
  6    6  Prmt-Dry     Prmt-Shl      No-CCI     Prmt-Dp     SDly-Dry    LDly-Dry
  2    1        1   1                   $ A.  CCI is dry and starts immediately
                1 * /1
          Prmt-Dry
  2    2        1   1                   $ B.  CCI occurs under 5 ft of water
                1 * /1
          Prmt-Shl
  1    3       10                       $ C.  CCI does not occur
                1
           No-CCI
  1    4       10                       $ D.  CCI occurs under 10 ft of water
                2
          Frmt-Dp
  2    5        1   1                   $ E.  CCI occurs after a delay,
                1 * /1                  $     cooling water not replenished
          SDly-Dry
  2    6        1   1                   $ F.  CCI occurs after a long delay
                1 * /1
          LDly-Dry
  4    4     SSPr         HiPr        ImPr        LoPr
  2    1        1   1                   $ A.  System setpoint pressure (2500)
                1 * /1
             SSPr
  1    2        3                       $ B.  1000-2000 psia
                2
             HiPr
  2    3        1   1                   $ C.  200-1000 psia
                1 * /1
             ImPr
  1    4        3                       $ D.  < 200 psia
                1
             LoPr
  6    6   VB-HPME      VB-Pour      VB-BtmHd       Alpha      Rocket       No-VB
  3    1        3   4   6               $ A.  HPME and DCH
                2 * 2 * 1
           VB-HPME
  3    2        3   4   6               $ B.  Molten pour at low pressure
                1 * 2 * 1
           VB-Pour
  2    3        1   1                   $ C.  Gross failure of bottom head
                1 * /1
           VB-BtmHd
  2    4        4   6                   $ D.  Alpha mode failure
                2 * 2
             Alpha
  2    5        1   1                   $ E.  Upward acceleration of vessel
                1 * /1
            Rocket
  1    6        4                       $ F.  No vessel breach
                1
             No-VB
  3    3      SGTR      SG-SRVO     No-SGTR
  2    1        1   1                   $ A.  SGTR occurs, secondary RVs reclose
                1 * /1
```

```
            SGTR
2   2          1   1               $ B.  SGTR, secondary RVs stuck open
               1 * /1
          SG-SRVO
2   3          1   1               $ C.  SGTR does not occur
               1 + /1
          No-SGTR
4   4     Hi-CCI     Med-CCI     Lo-CCI     No-CCI
1   1         10                   $ A.  CCI involves 70-100%
               2
           Hi-CCI
2   2          1   1               $ B.  CCI involves 30-70%
               1 * /1
          Med-CCI
2   3          1   1               $ C.  CCI involves 0-30%
               1 * /1
           Lo-CCI
1   4         10                   $ D.  No CCI occurs
               1
           No-CCI
2   2     Lo-ZrOx    Hi-ZrOx
2   1          1   1               $ A.  0-40% of core Zr was oxidized
               1 + /1
          Lo-ZrOx
2   2          1   1               $ B.  > 40% of core Zr was oxidized
               1 * /1
          Hi-ZrOx
4   4     Hi-HPME    Md-HPME     Lo-HPME     No-HPME
2   1          3   4               $ A.  Pct core ejected > 40%
               2 * 2
          Hi-HPME
2   2          1   1               $ B.  Pct core ejected 20-40%
               1 * /1
          Md-HPME
2   3          1   1               $ C.  Pct core ejected < 20%
               1 * /1
          Lo-HPME
2   4          3   4               $ D.  No HPME
               1 + 1
          No-HPME
4   4     Cat-Rpt     Rupture       Leak       No-CF
5   1          2   6   7   8  12       $ A.  Gross structural failure
               2 + 2 + 2 + 2 + 2
          Cat-Rpt
1   2         13                   $ B.  Hole > 7 ft2
               2
          Rupture
2   3          1   9               $ C.  Hole is about 0.1 ft2
               2 + 2
             Leak  or     BMT
8   4          1   2   6   7   8   9  12  13  $ D.  No containment failure
               1 * 1 * 1 * 1 * 1 * 1 * 1 * 1
           Bypass  or   No-CF
2   2     1-Hole     2-Holes
1   1          6                   $ A.  One hole - no natural circ.
```

```
              1
         1-Hole
1    2        6                     $ B.  Two holes - natural circulation
              2
         2-Holes
3    3   E2-InByP    E2-IpByP    E2-IByP
2    1        1    1                $ A.  No ice condenser bypass
              1 + /1
         E2-InByP
2    2        1    1                $ B.  10% ice bypass
              1 * /1
         E2-IpByP
2    3        1    1                $ C.  Total ice bypass
              1 * /1
         E2-IByP
3    3   I2-InByP    I2-IpByP    I2-IByP
2    1        1    1                $ A.  No ice condenser bypass
              1 + /1
         I2-InByP
2    2        1    1                $ B.  10% ice bypass
              1 * /1
         I2-IpByP
2    3        1    1                $ C.  Total ice bypass (or melted)
              1 * /1
         I2-IByP
4    4   ARF-Erly    ARF-E+L     ARF-Late     No-ARF
2    1        2    4                $ A.  Air return fans early only
              1 * 2
         ARF-Erly
2    2        2    4                $ B.                   early and late
              1 * 1
         ARF-E+L
2    3        1    1                $ C.                   late only
              1 * /1
         ARF-Late
1    4        2                     $ D.  No air return fans
              2
          No-ARF
```

LISTING 7

```
Sequoyah Source Term Binning -- PDSG-5, Transient
 14       CF-Time         Sprays          CCI       RCS-Pres      VB-Mode        SGTR
          Amt-CCI          Zr-Ox          HPME      CF-Size       RCS-Hole       E2-IC
            I2-IC         ARFans
  7    7   V-Dry           V-Wet      CF-Early      CF-atVB       CF-Late      CF-VLate
            NoCF
  2    1       1   1                          $ A.  Event V, not scrubbed
               1 * /1
           V-Dry
  2    2       1   1                          $ B.  Event V, scrubbed
               1 * /1
           V-Wet
  1    3       1                              $ C.  CF during core degradation
               2
          CF-Early
  3    4       5   6   7                      $ D.  CF at vessel breach
               2 + 2 + 2
          CF-atVB
  2    5       1   1                          $ E.  Late CF
               1 * /1
          CF-Late
  1    6      10                              $ F.  Very late CF
               2
          CF-VLate
  5    7       1   5   6   7  10              $ G.  No containment failure
               1 * 1 * 1 * 1 * 1
            NoCF
  8    8  Sp-Early      Sp-E+I      Sp-E+I+L     SpAlways     Sp-Late      Sp-L+VL
            Sp-VL      Sp-NonOp
  1    1       9                              $ A.  Sprays operate only early
               2
          Sp-Early
  2    2       1   1                          $ B.  Early and intermediate
               1 * /1
            Sp-E+I
  2    3       1   1                          $ C.  Early and late, not very late
               1 * /1
          Sp-E+I+L
  1    4       9                              $ D.  At all times
               1
          SpAlways
  2    5       1   1                          $ E.  Only late
               1 * /1
          Sp-Late
  2    6       1   1                          $ F.  Only late and very late
               1 * /1
          Sp-L+VL
  2    7       1   1                          $ G.  Only very late
               1 * /1
            Sp-VL
  2    8       1   1                          $ H.  Never
               1 * /1
```

```
        Sp-Never or Sp-Final
6   6   Prmt-Dry     Prmt-Shl      No-CCI      Prmt-Dp      SDly-Dry     LDly-Dry
2   1          1    1                    $ A.  CCI is dry and starts immediately
               1 * /1
        Prmt-Dry
2   2          1    1                    $ B.  CCI occurs under 5 ft of water
               1 * /1
        Prmt-Shl
1   3          8                         $ C.  CCI does not occur
               1
         No-CCI
1   4          8                         $ D.  CCI occurs under 10 ft of water
               2
        Prmt-Dp
2   5          1    1                    $ E.  CCI occurs after a delay,
               1 * /1                    $     cooling water not replenished
        SDly-Dry
2   6          1    1                    $ F.  CCI occurs after a long delay
               1 * /1
        LDly-Dry
4   4       SSPr         HiPr        ImPr         LoPr
1   1          3                         $ A.  System setpoint pressure (2500)
               1
            SSPr
2   2          1    1                    $ B.  1000-2000 psia
               1 * /1
            HiPr
2   3          1    1                    $ C.  200-1000 psia
               1 * /1
            ImPr
1   4          3                         $ D.  < 200 psia
               2
            LoPr
6   6   VB-HPME      VB-Pour     VB-BtmHd       Alpha       Rocket        No-VB
2   1          3    4                    $ A.  HPME and DCH
               1 * 2
        VB-HPME
2   2          3    4                    $ B.  Molten pour at low pressure
               2 * 2
        VB-Pour
2   3          1    1                    $ C.  Gross failure of bottom head
               1 * /1
        VB-BtmHd
2   4          1    1                    $ D.  Alpha mode failure
               1 * /1
          Alpha
2   5          1    1                    $ E.  Upward acceleration of vessel
               1 * /1
         Rocket
1   6          4                         $ F.  No vessel breach
               1
          No-VB
3   3       SGTR       SG-SRVO     No-SGTR
1   1          2                         $ A.  SGTR occurs, secondary RVs reclose
               2
```

```
            SGTR
2   2          1   1                 $ B.  SGTR, secondary RVs stuck open
               1 * /1
         SG-SRVO
1   3          2                     $ C.  SGTR does not occur
               1
         No-SGTR
4   4     Hi-CCI      Med-CCI      Lo-CCI      No-CCI
2   1          1   1                 $ A.  CCI involves 70-100%
               1 * /1
          Hi-CCI
2   2          1   1                 $ B.  CCI involves 30-70%
               1 * /1
         Med-CCI
1   3          8                     $ C.  CCI involves 0-30%
               2
          Lo-CCI
1   4          8                     $ D.  No CCI occurs
               1
          No-CCI
2   2    Lo-ZrOx      Hi-ZrOx
2   1          1   1                 $ A.  0-40% of core Zr was oxidized
               1 * /1
         Lo-ZrOx
2   2          1   1                 $ B.  > 40% of core Zr was oxidized
               1 + /1
         Hi-ZrOx
4   4    Hi-HPME      Md-HPME     Lo-HPME     No-HPME
2   1          3   4                 $ A.  Pct core ejected > 40%
               1 * 2
         Hi-HPME
2   2          1   1                 $ B.  Pct core ejected 20-40%
               1 * /1
         Md-HPME
2   3          1   1                 $ C.  Pct core ejected < 20%
               1 * /1
         Lo-HPME
2   4          3   4                 $ D.  No HPME
               2 + 1
         No-HPME
4   4    Cat-Rpt      Rupture        Leak       No-CF
2   1          5   6                 $ A.  Gr[illegible] structural failure
               2 + 2
         Cat-Rpt
1   2         10                     $ B.  Hole > 7 ft2
               2
         Rupture
2   3          1   7                 $ C.  Hole is about 0.1 ft2
               2 + 2
            Leak  or     BMT
5   4          1   5   6   7  10     $ D.  No containment failure
               1 * 1 * 1 * 1 * 1
          Bypass  or   No-CF
2   2     1-Hole      2-Holes
2   1          1   1                 $ A.  One hole - no natural circ.
```

```
              1 + /1
         1-Hole
 2   2        1   1                     $ B.  Two holes - natural circulation
              1 * /1
        2-Holes
 3   3  E2-InByP    E2-IpByP    E2-IByP
 2   1        1   1                     $ A.  No ice condenser bypass
              1 + /1
        E2-InByP
 2   2        1   1                     $ B.  10% ice bypass
              1 * /1
        E2-IpByP
 2   3        1   1                     $ C.  Total ice bypass (or melted)
              1 * /1
        E2-IByP
 3   3  I2-InByP    I2-IpByP    I2-IByP
 1   1        5                         $ A.  No ice condenser bypass
              1
        I2-InByP
 2   2        1   1                     $ B.  10% ice bypass
              1 * /1
        I2-IpByP
 1   3        5                         $ C.  Total ice bypass (or melted)
              2
        I2-IByP
 4   4  ARF-Erly    ARF-E+L     ARF-Late     No-ARF
 2   1        5   6                     $ A.  Air return fans early only
              2 + 2
        ARF-Erly
 2   2        5   6                     $ B.                  early and late
              1 * 1
        ARF-E+L
 2   3        1   1                     $ C.                  late only
              1 * /1
        ARF-Late
 2   4        1   1                     $ D.  No air return fans
              1 * /1
         No-ARF
```

LISTING 8

```
Sequoyah Source Term Binning -- PDSG-6, ATWS
 14       CF-Time      Sprays        CCI      RCS-Pres     VB-Mode       SGTR
          Amt-CCI       Zr-Ox        HPME     CF-Size      RCS-Hole      E2-IC
           I2-?        ARFans
  7   7   V-Dry         V-Wet      CF-Early   CF-atVB      CF-Late     CF-VLate
            NoCF
  2   1         1   1                    $ A.  Event V, not scrubbed
                1 * /1
           V-Dry
  2   2         1   1                    $ B.  Event V, scrubbed
                1 * /1
           V-Wet
  ?   3         2   3                    $ C.  CF during core degradation
                2 + 2
          CF-Early
  4   4         6   7   8   9            $ D.  CF at vessel breach
                2 + 2 + 2 + 2
          CF-atVB
  1   5        12                        $ E.  Late CF
                2
          CF-Late
  1   6        13                        $ F.  Very late CF
                2
          CF-VLate
  8   7         2   3   6   7   8   9  12  13   $ G.  No containment failure
                1 * 1 * 1 * 1 * 1 * 1 * 1 * 1
            NoCF
  8   8   Sp-Early     Sp-E+I     Sp-E+I+L   SpAlways    Sp-Late     Sp-L+VL
              Sp-VL    Sp-NonOp
  1   1        11                        $ A.  Sprays operate only early
                2
          Sp-Early
  2   2         1   1                    $ B.  Early and intermediate
                1 * /1
            Sp-E+I
  2   3         1   1                    $ C.  Early and late, not very late
                1 * /1
          Sp-E+I+L
  1   4        11                        $ D.  At all times
                1
          SpAlways
  2   5         1   1                    $ E.  Only late
                1 * /1
          Sp-Late
  2   6         1   1                    $ F.  Only late and very late
                1 * /1
          Sp-L+VL
  2   7         1   1                    $ G.  Only very late
                1 * /1
             Sp-VL
  2   8         1   1                    $ H.  Never
                1 * /1
```

```
          Sp-Never or Sp-Final
6    6    Prmt-Dry      Prmt-Shl      No-CCI      Prmt-Dp      SDly-Dry      LDly-Dry
2    1          1    1                        $ A.  CCI is dry and starts immediately
                1 * /1
          Prmt-Dry
2    2          1    1                        $ B.  CCI occurs under 5 ft of water
                1 * /1
          Prmt-Shl
1    3          10                            $ C.  CCI does not occur
                1
          No-CCI
1    4          10                            $ D.  CCI occurs under 10 ft of water
                2
          Prmt-Dp
2    5          1    1                        $ E.  CCI occurs after a delay,
                1 * /1                        $     cooling water not replenished
          SDly-Dry
2    6          1    1                        $ F.  CCI occurs after a long delay
                1 * /1
          LDly-Dry
4    4      SSPr          HiPr          ImPr          LoPr
2    1          1    1                        $ A.  System setpoint pressure (2500)
                1 * /1
            SSPr
1    2          4                             $ B.  1000-2000 psia
                2
            HiPr
2    3          1    1                        $ C.  200-1000 psia
                1 * /1
            ImPr
1    4          4                             $ D.  < 200 psia
                1
            LoPr
6    6    VB-HPME       VB-Pour       VB-BtmHd      Alpha       Rocket       No-VB
2    1          4    5                        $ A.  HPME and DCH
                2 * 2
          VB-HPME
2    2          4    5                        $ B.  Molten pour at low pressure
                1 * 2
          VB-Pour
2    3          1    1                        $ C.  Gross failure of bottom head
                1 * /1
          VB-BtmHd
2    4          1    1                        $ D.  Alpha mode failure
                1 * /1
            Alpha
2    5          1    1                        $ E.  Upward acceleration of vessel
                1 * /1
          Rocket
1    6          5                             $ F.  No vessel breach
                1
            No-VB
3    3      SGTR        SG-SRVO       No-SGTR
1    1          1                             $ A.  SGTR occurs, secondary RVs reclose
                2
```

```
            SGTR
 2   2         1    1                  $ B.  SGTR, secondar; RVs stuck open
               1 * /1
        SG-SRVO
 1   3         1                       $ C.  SGTR does not occur
               1
        No-SGTR
 4   4   Hi-CCI      Med-CCI      Lo-CCI      No-CCI
 1   1        10                       $ A.  CCI involves 70-100%
               2
         Hi-CCI
 2   2         1    1                  $ B.  CCI involves 30-70%
               1 * /1
        Med-CCI
 2   3         1    1                  $ C.  CCI involves 0-30%
               1 * /1
         Lo-CCI
 1   4        10                       $ D.  No CCI occurs
               1
         No    1
 2   2  Lo     x       Hi-ZrOx
 2   1         1    1                  $ A.  0-40% of core Zr was oxidized
               1 * /1
        Lo-ZrOx
 2   2         1    1                  $ B.  > 40% of core Zr was oxidized
               1 + /1
        Hi-ZrOx
 4   4  Hi-HPME      Md-HPME      Lo-HPME      No-HPME
 2   1         4    5                  $ A.  Pct core ejected > 40%
               2 * 2
        Hi-HPME
 2   2         1    1                  $ B.  Pct core ejected 20-40%
               1 * /1
        Md-HPME
 2   3         1    1                  $ C.  Pct core ejected < 20%
               1 * /1
        Lo-HPME
 2   4         4    5                  $ D.  No HPME
               1 + 1
        No-HPME
 4   4  Cat-Rpt      Rupture          Leak        No-CF
 3   1         3    8  12              $ A.  Gross structural failure
               2 + 2 + 2
        Cat-Rpt
 3   2         6    7  13              $ B.  Hole > 7 ft2
               2 + 2 + 2
        Rupture
 2   3         2    9                  $ C.  Hole is about 0.1 ft2
               2 + 2
           Leak  or     BMT
 8   4         2    3   6   7   8   9  12  13  $ D.  No containment failure
               1 * 1 * 1 * 1 * 1 * 1 * 1 * 1
         Bypass  or   No-CF
 2   2   1-Hole      2-Holes
 1   1         6                       $ A.  One hole - no natural circ.
```

```
              1
         1-Hole                        $ B.  Two holes - natural circulation
1   2         6
              2
        2-Holes
3   3   E2-InByP    E2-IpByP    E2-IByP
2   1         1   1                    $ A.  No ice condenser bypass
              1 + /1
        E2-InByP
2   2         1   1                    $ B.  10% ice bypass
              1 * /1
        E2-IpByP
2   3         1   1                    $ C.  Total ice bypass (or melted)
              1 * /1
        E2-IByP
3   3   I2-InByP    I2-IpByP    I2-IByP
2   1         1   1                    $ A.  No ice condenser bypass
              1 + /1
        I2-InByP
2   2         1   1                    $ B.  10% ice bypass
              1 * /1
        I2-IpByP
2   3         1   1                    $ C.  Total ice bypass (or melted)
              1 * /1
        I2-IByP
4   4   ARF-Erly    ARF-E+L    ARF-Late    No-ARF
1   1         3                        $ A.  Air return fans early only
              2
        ARF-Erly
1   2         3                        $ B.                    early and late
              1
        ARF-E+L
2   3         1   1                    $ C.                    late only
              1 * /1
        ARF-Late
2   4         1   1                    $ D.  No air return fans
              1 * /1
        No-ARF
```

APPENDIX D

CATALYTIC HYDROGEN IGNITERS

APPENDIX D

CATALYTIC HYDROGEN IGNITERS

Development work on catalytic igniters has progressed in both the United States and the Federal Republic of Germany over the last couple of years.[D-1, D-2] In the U.S., the prime developer has been Sandia National Laboratories in Livermore, CA. They have developed a prototype catalytic igniter that requires no electric power and can ignite mixtures as lean as 5.5% hydrogen. The igniter is susceptible to failure from high gas velocities, water spray, steam and iodine-containing compounds, however shielding and semi-permeable coatings could overcome these problems. (Recent, yet to be published work, has succeeded in developing a fin-type, wet-proofed igniter.) Catalytic igniter development has also been carried out by Siemens/Kraftwerk Union (KWU). However, the KWU igniter is a fully-engineered device with an enclosure for the igniter element, which has been tested and qualified for use in German reactors. KWU has also developed a battery powered spark igniter for use in hydrogen control applications. This spark igniter has an adjustable actuation temperature and pressure and a discharge life for the batteries of at least five days at 130°C.

REFERENCES

D-1. L. R. Thorne, J. V. Volponi, and W. J. McLean, *Platinum Catalytic Igniters for Lean Hydrogen-Air Mixtures*, NUREG/CR-5086, September 1988.

D-2. R. Hecht, "Catalytic Igniter, Spark Igniter," *presented at the Catalytic Igniter Evaluation Meeting sponsored by the Electric Power Research Institute, Palo Alto, California, November 21, 1988.*

APPEND.X E

FRONT END ISSUES ANALYSIS

APPENDIX E

FRONT END ISSUES ANALYSIS

ECR Risk Sensitivity

Sensitivity analyses were performed to estimate the effect on both core melt frequency and risk of two approaches for improving the reliability of emergency coolant recirculation (ECR). Pending availability of the updated Sequoyah containment analysis,[E-1] interim sensitivity calculations were made by combining the updated version of the core damage analysis[E-2] with the original version of the containment and consequence analyses.[E-3]

Two possible modifications were evaluated as Case Studies and these are discussed as follows. Case-1 examined the benefits of improving the performance of the reactor operators (i.e. reducing the human error probabilities or HEPs) in emergency core coolant system (ECCS) realignment from high pressure injection (HPI) to high pressure recirculation (HPR). The human errors that were identified in Reference E-3, as important to the core damage frequency are listed in Table E-1. Case-2 analyzes the benefits of the capability of prolonging HPI during small LOCAs by refilling the refueling water storage tank (RWST). This would eliminate the need to switch to HPR (Note this was not considered effective for the interfacing system LOCA sequences, see following section). Tables E-2 and E-3 display the results of these two cases respectively, for different levels of improvement.

Possible ECR Improvements

It has been proposed that refilling the RWST would improve the severe accident performance of Ice Condenser type of plants by extending the amount of time available to the plant operators for carrying out required emergency procedures. Although the basic idea has merit, a number of influencing factors must be accounted for to actually produce a significant benefit in terms of risk reduction. This proposed improvement would benefit those accident sequences that involve a loss-of-coolant accident (LOCA), with successful emergency coolant injection (ECI) but with a subsequent failure of emergency coolant recirculation (ECR). These types of sequences were found to be significant for both the Sequoyah core melt frequency and its risk. Also, it is important to note that this class of sequences might include the interfacing system LOCA (ISLOCA). In the ISLOCA sequence, the lost coolant bypasses containment and therefore results in a failure to fill the containment sump, which is the source of water for ECR. However, for this option to be effective for the ISLOCA sequences, a virtual inexhaustible supply of water must be provided, and the consequences of the ISLOCA flooding areas of the plant must be accounted for.

One aspect of refilling the RWST centers on the rate at which makeup can be provided. The major motivation behind this actions originates from the relatively rapid rate at which the RWST drains during a postulated small-LOCA. The specific accident scenario of interest involves a LOCA of such a size that the RCS does not depressurize, but does result in the containment pressure setpoint (typically about 3 psig) being reached that actuates the containment spray system (CSS). The large flow rate of the CSS pumps (about 4000 gpm for each of two pumps) results in the rapid depletion of the RWST to the low-low level at which time the operators are required to realign the safety injection system for high pressure recirculation (this time has been estimated in support of the NUREG-1150 effort at about 30 minutes, see section 4.8.4.3 of NUREG/CR-4550, Rev.1, Vol.5). The low-pressure portions of the safety injection system realign to recirculation automatically, however manual actions are needed to align the high pressure pump suction to the low pressure system discharge (i.e., the normal alignment for HPR). Normal makeup for the RWST, is provided via the CVCS and is capable of supplying approximately 140 gpm of borated water. Therefore, for this strategy to be effective, either the CSS flow needs to be severely limited or an alternate means of makeup is required.

In the FSAR LOCA analyses, four of the five ice condenser plants (D. C. Cook being the exception), rely upon the CSS for containment pressure suppression only, while the ice condenser system provides the containment atmosphere radionuclide removal function. It therefore appears feasible that for these four plants, the CSS operation could be delayed without major complications to the DBA analysis. However, detailed containment calculations would be needed to ensure that the DBA containment pressure remains below the design pressure (12 to 15 psig). These containment calculations would provide a re-estimate of the peak containment pressure reached during a severe accident, which would likely exceed the original design basis accident estimated peak pressure of 10.8 psig (note that the actual failure pressures for three of the five ice condenser containments have already been estimated at from 60 to 120 psig).

Another alternative is to lower the containment pressure setpoint for actuation of the containment air recirculation (CAR) fans, which circulate the containment atmosphere from the lower compartment through the ice chest to the upper compartment and then back to the lower compartment. Currently the fans actuate at the same time the sprays do, at a hi-hi containment pressure (typically 3 psig). If instead, the CAR fans were started on the Safety Injection (SI) signal, at a hi containment pressure of 1 psig, it might extend the time it takes for the containment pressure to reach the 3 psig setpoint and CS actuation. This would likely provide additional time (hence improve their reliability) for the operators in responding to the accident, including performing the realignment to recirculation. However, detailed containment modeling calculations would need to be done to accurately estimate the effect of this modification.

If none of the above options are practical, the last alternative is to install a new capability for refilling the RWST at very high flow rates (at least 4000 gpm). Further, the makeup should be borated water to ensure reactor subcriticality. One possible source for providing RWST makeup could be the fire protection system, modified to filter and borate the water before being added to the RWST. This option has the advantage of: (a) large flow rates, (b) a virtually unlimited supply of water (although a means of borating the water would need to be added), and (c) the pumps are already in place, are (for Sequoyah at least) powered from emergency sources, and seismically qualified. This modification also has the benefit of potentially being effective during ISLOCA sequences, which for Sequoyah are the dominant contributors to plant risk. However, before estimating the benefit with regards to the ISLOCA, the effects of possible flooding, as a result of the ISLOCA, on required equipment would need to be analyzed.

Table E-1. Human Errors Dominating the Failure to Perform the Realignment from HPI to HPR for Sequoyah.

Event ID	Description	Base Case HEP
HPR-XHE-FO-SIMIN	Operator fails to close SI miniflow lines to RWST during S_2 LOCA.	2.85E-3
HPR-XHE-FO-SIMN2	Operator fails to close SI miniflow lines to RWST during S_3O_d sequences.	2.51E-3
HPR-XHE-FO-V8V11	Operator fails to open HPR flow control valves 63-8 and 63-11.	2.05E-3

Table E-2. Sequoyah Risk Sensitivity Analysis to Improving Operator Performance in Realigning from HPI to HPR. (Risk per reactor year.)

	Base Case	Sensitivity Cases			
Factor Reduction --> in HEPs	0.0	0.1	0.5	0.9	1.0
Core Melt Freq.	5.90E-05	5.62E-05	4.53E-05	3.44E-05	3.17E-05
Early Fatalities	3.7E-05	3.7E-05	3.6E-05	3.6E-05	3.6E-05
Early Injuries	8.8E-05	8.8E-05	8.6E-05	8.4E-05	8.3E-05
Latent Cancers	4.4E-02	4.3E-02	4.1E-02	4.0E-02	3.9E-02
Ind. Risk of Fat.	1.0E-07	1.0E-07	9.9E-08	9.8E-08	9.7E-08
Offsite Costs ($)	1.3E+04	1.2E+04	1.2E+04	1.1E+04	1.1E+04
Pop. Dose (man-rem)	8.7E+01	8.6E+01	8.1E+01	7.6E+01	7.5E+01

a. These Sensitivity caluclations represent unspecified improvements in the performance of the human operator accomplishing the realignment from high pressure injection to high pressure recirculation. These improvements could be accomplished through such things as better training or better procedures (although it is unrealistic to expect a reduction factor of 1.0, i.e., reducing the HEP to 0.0.

b. The factor reduction in HEP is utilized in the following manner: new HEP = (X)HEP, where X represents the reduction fac'or listed in the table.

Table E-3. Sequoyah Risk Sensitivity Analysis to Refilling the RWST for Continued HPI Operation (i.e., obviating HPR failures) (Risk per reactor year.)

	Base Case	Sensitivity Cases			
Probability of Successfully --> Refilling RWST	0.0	0.1	0.5	0.9	1.0
Core Melt Freq	5.90E-05	5.50E-05	3.93E-05	2.36E-05	1.96E-05
Early Fatalities	3.7E-05	3.7E-05	3.5E-05	3.4E-05	3.4E-05
Early Injuries	8.8E-05	8.7E-05	8.2E-05	7.7E-05	7.6E-05
Latent Cancers	4.4E-02	4.2E-02	3.8E-02	3.3E-02	3.2E-02
Ind. Risk of Fat.	1.0E-07	1.0E-07	9.6E-08	9.2E-08	9.1E-08
Offsite Costs ($)	1.3E+04	1.2E+04	1.1E+04	9.1E+03	8.7E+03
Pop. Dose (man-rem)	8.7E+01	8.4E+01	7.1E+01	5.8E+01	5.5E+01

a. This sensitivity examines the idealistic situation where the RWST can be refilled and a source of injection water maintained indefinitely. The different cases estimate the effect of different levels of reliability for this process. That is, in the base case, no credit is assumed for refilling the RWST, therefore, the probability is shown as 0.0. the sensitivity case represented as 1.0 estimates the effect on risk of a perfectly reliable system for refilling the RWST, which translates into the complete removal of all HPR failures from the sequence cutsets.

REFERENCES

E-1. J. J. Gregory et al., *Evaluation of Severe Accident Risks: Sequoyah Unit 1, Sandia National Laboratories,* NUREG/CR-4551, Volume 5, Revision 1, SAND86-1309, December 1990.

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E-3. A. S. Benjamin et al., *Evaluation of Severe Accident Risks and the Potential for Risk Reduction: Sequoyah Power Station, Unit 1, Sandia National Laboratories,* NUREG/CR-4551, Volume 2, Draft Report for Comment, SAND86-1309, February 1987.

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

An evaluation of a Pressurized Water Reactor (PWR) ice condenser containment was performed. In this evaluation, simplified containment event trees (SCETs) were developed that utilized the vast storehouse of information generated by the NRC's Draft NUREG-1150 effort. Specifically, the computer programs and data files produced by the NUREG-1150 analysis of Sequoyah were used to electronically generate SCETs, as opposed to the NUREG-1150 accident progression event trees (APETs). This simplification was performed to allow graphic depiction of the SCETs in typical event tree format, which facilitates their understanding and use. SCETs were developed for five of the seven plant damage state groups (PDSGs) identified by the NUREG-1150 analyses, which includes: both short- and long-term station blackout sequences (SBOs), transients, loss-of-coolant accidents (LOCAs), and anticipated transient without scram (ATWS). Steam generator tube rupture (SGTR) and event-V PDSGs were not analyzed because of their containment bypass nature. After being benchmarked with the APETs, in terms of containment failure mode and risk, the SCETs were used to evaluate a number of potential containment modifications. The modifications were examined for their potential to mitigate or prevent containment failure from hydrogen burns or direct impingement on the containment by the core, (both factors identified as significant contributors to risk in the NUREG-1150 Sequoyah analysis). However, because of the relatively low baseline risk postulated for Sequoyah (i.e., 12 person-rems per reactor year), none of the potential modifications appear to be cost effective.

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