Risk Assessment of Operational Events

Handbook

Volume 4 – Shutdown Events

Revision 1.0

April 2011

SDP Phase 3 ● ASP ● MD 8.3

TABLE OF CONTENTS

ACRONYMS

AC	alternate current
AFW	auxiliary feedwater
ASP	accident sequence precursor
ATHEANA	a Technique for Human Event Analysis
ATWS	anticipated transient without scram
BWR	boiling-water reactor
CCDP	conditional core damage probability
CD	core damage
CDF	core damage frequency
CDP	core damage probability
DH	decay heat
DHR	decay heat removal
DT	duration time
ET	event tree
FT	fault tree
HEP	human error probability
HFE	human failure event
HHSI	high-head safety injection
IMC	inspection manual chapter
LOI	loss of inventory
LOOP	loss of offsite power
LORHR	loss of residual heat removal
LPI	low-pressure injection
LTOP	low-temperature over-pressurization
MCR	main control room
MMG	model maker's guideline (shutdown)
MWHUT	miscellaneous waste holdup tank
NRC	U.S. Nuclear Regulatory Commission
OD	over-drain
POS	plant operating state
PRA	probabilistic risk assessment
PWR	pressurized-water reactor
RCS	reactor coolant system
RHR	residual heat removal

SAPHIRE	Systems Analysis Programs for Hands-on Integrated Reliability Evaluations
SD	Shutdown
SDP	Significance determination process
SG	steam generator
SI	safety injection
SPAR	Standardized Plant Analysis Risk
SRA	senior reactor analyst
SRO	senior reactor operator
STW	sequence time window
TDP	turbine-driven pump
T/M	test or maintenance

1.0 Introduction

1.1 Objectives

The first objective of the Risk Assessment of Operational Events Handbook (sometimes known as "RASP Handbook" or "handbook") is to document methods and guidance that U.S. Nuclear Regulatory Commission (NRC) staff could use to achieve more consistent results when performing risk assessments of operational events and licensee performance issues.

The second objective is to provide analysts and Standardized Plant Analysis Risk (SPAR) model developers with additional guidance to ensure that the SPAR models used in the risk analysis of operational events represent the as-built, as-operated plant to the extent needed to support the analyses.

This handbook represents best practices based on feedback and experience from the analyses of over 600 precursors of events dating back to 1969 in the Accident Sequence Precursor (ASP) Program and numerous Significance Determination Process (SDP) Phase 3 analyses (since 2000).

1.2 Scope of the Handbook

The scope of the handbook is provided below.

- ***Applications.*** The methods and processes described in the handbook can be primarily applied to risk assessments for Phase 3 of the SDP, the ASP Program, and event assessments under the NRC's Incident Investigation Program (in accordance with Management Directive 8.3). The guidance for the use of SPAR models and Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE) software package can be applied in the risk analyses for other regulatory applications, such as the Generic Issues Program and special risk studies of operational experience.

- ***Relationships to program requirements.*** This handbook is intended to provide guidance for implementing requirements contained in program-specific procedures, such as Inspection Manual Chapter (IMC) 0609, "Significance Determination Process," and IMC 0309, "Reactive Inspection Decision Basis for Reactors." It is not the scope of this handbook to repeat program-specific requirements in the handbook, since these requirements may differ among applications and may change as programs evolve. Program-specific requirements supersede guidance in this handbook.

- ***Deviations from methods and guidance.*** Some unique events may require an enhancement of an existing method or development of new guidance. Deviations from methods and guidance in this handbook may be necessary for the analysis of atypical events. However, such deviations should be adequately documented in the analysis to allow for the ease of peer review. Changes in methodologies and guidance will be reflected in future revisions of this handbook.

1.3 Audience for the Handbook

The principal users of this handbook are senior reactor analysts (SRAs) and headquarters risk analysts involved with the risk analysis of operational events. It is assumed that the analysts using this handbook have received probabilistic risk assessment (PRA) training at the SRA qualification level. Analysts using this handbook should be familiar with the risk analysis of operational events, SAPHIRE software package, and key SPAR model assumptions and technical issues. Although, this handbook could be used as a training guide, it is assumed that an analyst either has completed the NRC course "Risk Assessment in Event Evaluation" (Course Number P-302) or has related experience.

1.4 Handbook Content

The revised handbook includes three volumes, designed to address Internal Events (Volume 1), External Events (Volume 2), SPAR Model Reviews (Volume 3), and Shutdown Events (Volume 4). Each volume is complementary to the others. The scope of these volumes is as follows:

- ***Volume 1, Internal Events.*** Volume 1, "Internal Events," provides generic methods and processes to estimate the risk significance of initiating events (e.g., reactor trips, losses of offsite power) and degraded conditions (e.g., a failed high pressure injection pump, failed emergency power system) that have occurred at nuclear power plants.[1]

  Specifically, this volume provides guidance on the following analysis methods:

  - Exposure Time Determination and Modeling
  - Failure Determination and Modeling
  - Mission Time Modeling
  - Modeling Recovery and Repair Actions in Event Assessment
  - Multi-Unit Considerations Modeling
  - Treatment of Common-Cause Failures in Events Assessment *(Future)*

  In addition, the appendices provide further guidance on the following analysis topics:

  - Road Map – Risk Analysis of Operational Events

  Although, the guidance in this volume of the handbook focuses on the analysis of internal events during at-power operations, the basic processes for the risk analysis of initiating events and degraded conditions can be applied to external events, as well as events occurring during shutdown operations.

- ***Volume 2, External Events.*** Volume 2, "External Events," provides methods and guidance for the risk analysis of initiating events and conditions associated with external events. External events include internal flooding, internal fire, seismic, external flooding, external fire, high winds, tornado, hurricane, and others. This volume is intended to complement Volume 1 for Internal Events and Volume 4 for Shutdown Events.

  Specifically, this volume provides the following guidance:

  - Internal Flood Modeling and Risk Quantification

[1] In this handbook, "initiating event" and "degraded condition" are used to distinguish an incident involving a reactor trip demand from a loss of functionality during which no trip demand occurred. The terms "operational event" and "event," when used, refer to either an initiating event or a degraded condition.

- Internal Fire Modeling and Risk Quantification
- Seismic Event Modeling and Seismic Risk Quantification
- Other External Events Modeling and Risk Quantification

- ***Volume 3, SPAR Model Reviews.*** Volume 3, "SPAR Model Reviews," provides analysts and SPAR model developers with additional guidance to ensure that the SPAR models used in the risk analysis of operational events represent the as-built, as-operated plant to the extent needed to support the analyses. This volume provides checklists that can be used following modifications to SPAR models that are used to perform risk analysis of operational events. These checklists were based on the PRA Review Manual (NUREG/CR-3485, Ref. 1-1), the PRA Standard [ASME RA-S-2005 (Ref. 1-2) and Regulatory Guide 1.200 (Ref. 1-3)], and experiences and lessons learned from SDP and ASP analyses.

  In addition, this volume summarizes key assumptions in a SPAR model and unresolved technical issues that may produce uncertainties in the analysis results. The importance of these assumptions or issues depends on the sequences and cut sets that were impacted by the operational event. Additionally, plant-specific assumptions and issues may play an even larger role in the analysis uncertainties. This volume is intended to complement Volume 1 for Internal Events, Volume 2 for External Events, and Volume 4 for Shutdown Events, or whenever a modification to the SPAR model is required.

- ***Volume 4, Shutdown Events.*** Volume 4, "Shutdown Events," provides methods and guidance for the risk analysis of initiating events and conditions associated with plant shutdown (SD) events. The current scope is limited to shutdown events at select plant operating states for pressurized water reactor (PWR) and boiling water reactor (BWR) plants (e.g., hot shutdown, cold shutdown, refueling outage, and mid-loop operations for PWRs). This guide does not address the risk assessments of low-power and large early release frequency events.

  Specifically, this volume addresses the following four cases:

  - Initiating Event Analysis
  - Plant Condition Analysis Involving One Plant Operating State (POS)
  - Plant Condition Analysis Involving Multiple POSs
  - Special Cases (with no pre-defined POS available for the shutdown scenario of interest).

  Additionally, this volume provides insightful discussions on a set of frequently encountered issues to consider when developing shutdown risk models. This set of issues include (i) treatment of operator actions and human error dependencies, (ii) equipment test and maintenance configurations, and (iii) decay heat loads during time between shutdown and event initiation. This volume is intended to complement Volume 1 for Internal Events and Volume 2 for External Events.

1.5 Companion References to the Handbook

Guidance in the three volumes of the handbook often refers to other references, as applicable to the application. A bibliography of current technical references used in the risk analysis of operational events is provided in Volume 3, in which most of the documents are referenced in individual sections throughout the handbook.

Key companion references that are an extension to this handbook include:

- PRA Standard (Refs. 1-2 and 1-3)
- NUREG/CR-6823, "Handbook of Parameter Estimation for Probabilistic Risk Assessment" (Ref. 1-4)
- NUREG-1792, "Good Practices for Implementing Human Reliability Analysis" (Ref. 1-5)
- NUREG-1842, "Evaluation of Human Reliability Analysis Methods Against Good Practices" (Ref. 1-6)
- NUREG/CR-6883, "SPAR-H Human Reliability Analysis Method" (Ref. 1-7)
- NUREG-1624, Rev. 1, "Technical Basis and Implementation Guide for A Technique for Human Event Analysis (ATHEANA)" (Ref. 1-8)
- NUREG-1880, "ATHEANA User's Guide" (Ref. 1-9)
- NUREG/CR-6850, "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities, Volume 2: Detailed Methodology" (Ref. 1-10)
- Handbook for Phase 3 Fire Protection (FP) Significance Determination Process (SDP) Analysis (Ref. 1-11)
- Basic SAPHIRE training manual (Ref. 1-12)
- Advanced SAPHIRE training manual (Ref. 1-13)
- Plant-specific SPAR model manual

1.6 Questions, Comments, and Suggestions

Questions, comments, and suggestions should be directed to the following:

From internal NRC staff and NRC contractors:

- Volume 1, Internal Events
  - Chris Hunter, 301-415-7575, Christopher.Hunter@nrc.gov
  - See-Meng Wong, 301-415-1125, See-Meng.Wong@nrc.gov
- Volume 2, External Events
  - Selim Sancaktar, 301-215-7572, Selim.Sancaktar@nrc.gov
- Volume 3, SPAR Model Reviews
  - Peter Appignani, 301-251-7608, Peter.Appignani@nrc.gov
- Volume 4, Shutdown Events
  - Selim Sancaktar, 301-215-7572, Selim.Sancaktar@nrc.gov

From external NRC stakeholders (e.g., public, licensees):

- All handbook volumes; Significant Determination Process
  - Steve Vaughn, 301-415-3640, Stephen.Vaughn@nrc.gov

1.7 References

1-1. U.S. Nuclear Regulatory Commission, "PRA Review Manual," NUREG/CR-3485, September 1985. (ADAMS Accession Number ML063550234)

1-2. American Society of Mechanical Engineers, "Standard for Probabilistic Risk Assessment for Nuclear Power Plant Applications," ASME RA-S-2005, 2005.

1-3. U.S. Nuclear Regulatory Commission, Regulatory Guide 1.200, "An Approach for Determining the Technical Adequacy of Probabilistic Risk Assessment Results for Risk-Informed Activities," Revision 1, January 2007. http://www.nrc.gov/reading-rm/doc-collections/reg-guides/power-reactors/active/01-200/01-200r1.pdf

1-4. U.S. Nuclear Regulatory Commission, "Handbook of Parameter Estimation for Probabilistic Risk Assessment," NUREG/CR-6823, September 2003. http://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6823/

1-5. U.S. Nuclear Regulatory Commission, "Good Practices for Implementing Human Reliability Analysis," NUREG-1792, April 2005. http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1792/

1-6. U.S. Nuclear Regulatory Commission, "Evaluation of Human Reliability Analysis Methods against Good Practices," NUREG-1842, March 2006. http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1842/

1-7. U.S. Nuclear Regulatory Commission, "The SPAR-H Human Reliability Analysis Method," NUREG/CR-6883, August 2005. http://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6883/

1-8. U.S. Nuclear Regulatory Commission, "Technical Basis and Implementation Guide for A Technique for Human Event Analysis (ATHEANA)," NUREG-1624, Rev. 1, May 2000. http://www.nrc.gov/reading-rm/doc-collections/nuregs/pubs/

1-9. U.S. Nuclear Regulatory Commission, "ATHEANA User's Guide," NUREG-1880, June 2007. http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1880/

1-10. U.S. Nuclear Regulatory Commission, "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities, Volume 2: Detailed Methodology," NUREG/CR-6850, September 2005. http://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6850/

1-11. U.S. Nuclear Regulatory Commission, "Handbook for Phase 3 Fire Protection (FP) Significance Determination Process (SDP) Analysis," December 2005. (ADAMS Accession Number ML053620267)

1-12. Idaho National Laboratory, "SAPHIRE Basics - An Introduction to Probabilistic Risk Assessment via the Systems Analysis Program for Hands-On Integrated Reliability Evaluations (SAPHIRE) Software," Current Revision.

1-13. Idaho National Laboratory, "Advanced SAPHIRE - Modeling Methods for Probabilistic Risk Assessment via the Systems Analysis Program for Hands-On Integrated Reliability Evaluations (SAPHIRE) Software," Current Revision.

2.0 Scope and Summary

2.1 Scope

The current scope of this Handbook is limited to shutdown events at different plant operating states (POSs) listed below and calculation of core damage frequency (CDF) values only. It does not address the risk assessments of low power and large early release frequency events. POS applicable to BWRs and PWRs are defined as the following:

- ***BWR POSs***
  - Mode 3—Hot Shutdown
  - Mode 4—Cold Shutdown
  - Mode 5—Refueling Outage

- ***PWR POSs***
  - Mode 3—Hot Shutdown
  - Mode 4—Cold Shutdown
  - Mode 5—Mid-Loop Operations
  - Mode 6—Refueling Outage

2.2 Summary

This document contains RASP Handbook guidance for plant event and condition analyses of shutdown events, using SPAR models. The document addresses four categories of analyses:

1. Initiating event analysis [calculate conditional core damage probability (CCDP)].
2. Plant condition analysis involving one POS [calculate core damage probability (CDP)].
3. Plant condition analysis involving multiple POSs (calculate CDP).
4. Special cases (no predefined POS available for the SD scenario of interest).

In this document, the terms for “initiating event analysis” and “event analysis” are used interchangeably.

Experience with performing actual SDP Phase 3 and ASP analyses of SD events over the last few years indicate that whenever a need for a plant-specific shutdown analysis arises, either there is no SPAR-SD model available; or it is available but is not updated; or is not suitable for the case being analyzed. Therefore, a case-specific model needs to be constructed in a short time frame. It is expected that this Handbook should be used in conjunction with the SD Model Maker’s Guide (MMG) by experienced PRA analysts only. This Handbook guidance and the MMG are intended to capture the technology and knowledge base accumulated on this subject, and relies on the analyst's proficiency with the competent use of the SAPHIRE software. The accompanying event tree (ET) library and the human error probability (HEP) library are also intended to capture the accumulated knowledge base and support the consistent application of the technology.

2.3 Currently Available Tools, Models and Documents

The following tools, models, and documents available for quantifying SD risk in addition to this document:

- SAPHIRE software to run the models (Ref. 2-1);
- SPAR Shutdown Model Maker's Guideline (MMG) (Ref. 2-2)
- Shutdown event tree template library (Ref. 2-2)
- Shutdown operator actions and human error probability (HEP) library (Ref. 2-2)
- SPAR shutdown models for a limited number of plants (Ref. 2-2)

Figure 2-1 provides a visual summary of elements available to an analyst.

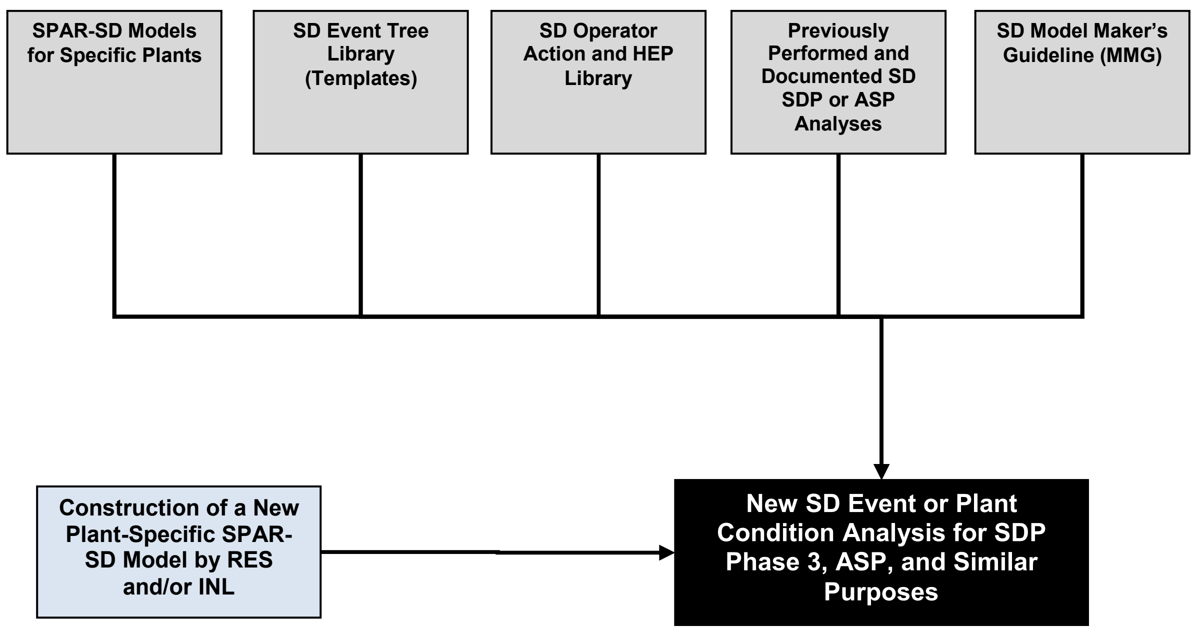


Figure 2-1. Elements Available to an Analyst for SD

2.4 Status of SD Models

The current version of this Handbook guidance is provided for use with the existing SPAR-SD models available to NRC analysts. Currently, there are eight SPAR-SD models in the SAPHIRE User Group webpage (Ref. 2-1):

Plant Name	Plant Type	Status
Davis-Besse	PWR/BW	SAPHIRE8 compatible, final version
Columbia	BWR	SAPHIRE8 compatible, final version
Seabrook	PWR/W	SAPHIRE8 compatible, final version
Turkey Point	PWR/W	SAPHIRE8 compatible, final version
Comanche Peak	PWR/W	SAPHIRE8 compatible, final version

Brunswick	BWR	SAPHIRE8 compatible, final version
San Onofre	PWR/CE	SAPHIRE8 compatible, final version
Grand Gulf	BWR	SAPHIRE8 compatible, draft version

For each SPAR-SD model, the SD model documents (in WORD and EXCEL files), HEP calculations, etc. can be found in the SPAR model folder named Shared\Documents\XXXX-SD-Docs, where XXXX refers to the acronym for the plant in question.

Earlier SPAR-SD models utilized a set of identical SD event trees. These models are characterized by a main event tree named SD which defines plant operating states and transfers into sub event trees for the POSs. The event tree nodes are defined formally; the plant specific nature of these nodes is introduced in fault tree logic. This approach is no longer used since it is shown to be of limited benefit for actual SDP and ASP analyses. However, since some of the current models contain also this form (in addition to the new ET templates by SD initiating events), some examples for these models are mentioned in the Handbook.

2.5 Examples of “Old” versus “New” Models

Figure 2-2 shows the old model ETs for the Columbia plant; they are highlighted in the list. Figure 2-3 shows the “new” SD event trees for the same plant. Note that both models coexist for this plant. Figure 2-4 shows the “new” ET models for the Davis Besse plant. Note that the “old” SD ET models are removed for this plant. Eventually, all “old” SD ET models will be removed.

The new SD event tree models always start with the name SD- and can be run individually, just like the ETs for internal events.

2.6 New Tool (Shutdown Core Uncovery Calculator)

An MS EXCEL based new tool has been created for calculation of core uncovery times for given configurations of water volumes above the core during a shutdown POS. This calculator (Ref. 2-3) allows for accounting of decay heat production rate, losses due to boiling, and losses due to reactor coolant system (RCS) boundary breaks (if applicable). The calculator can also be used in a stand-alone mode to estimate decay heat rates after N hours from shutdown. The uncovery times calculated by this calculator can be used to estimate time windows available for operator actions during various SD POSs. Figures 2-5, 2-6, and 2-7 illustrate worksheets from the calculator workbook. An user’s guide and overview are provided in Ref. 2-2 (refer to documents titled Shutdown Core Uncovery Calculator and Shutdown Calculator Presentation).

Figure 2-2. “Old” ET Models for Columbia Plant

Figure 2-3. "New" ET Models for Columbia Plant

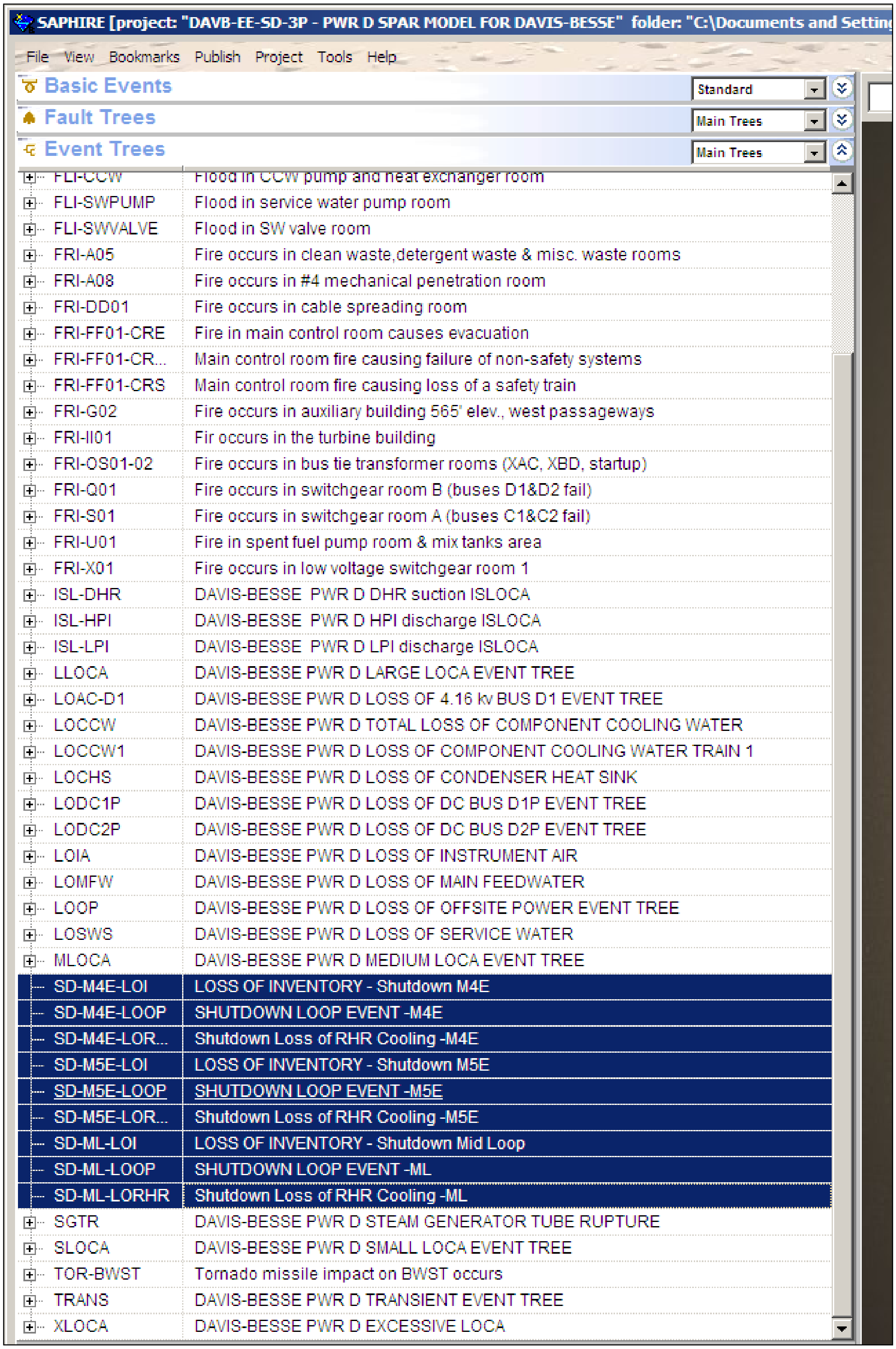


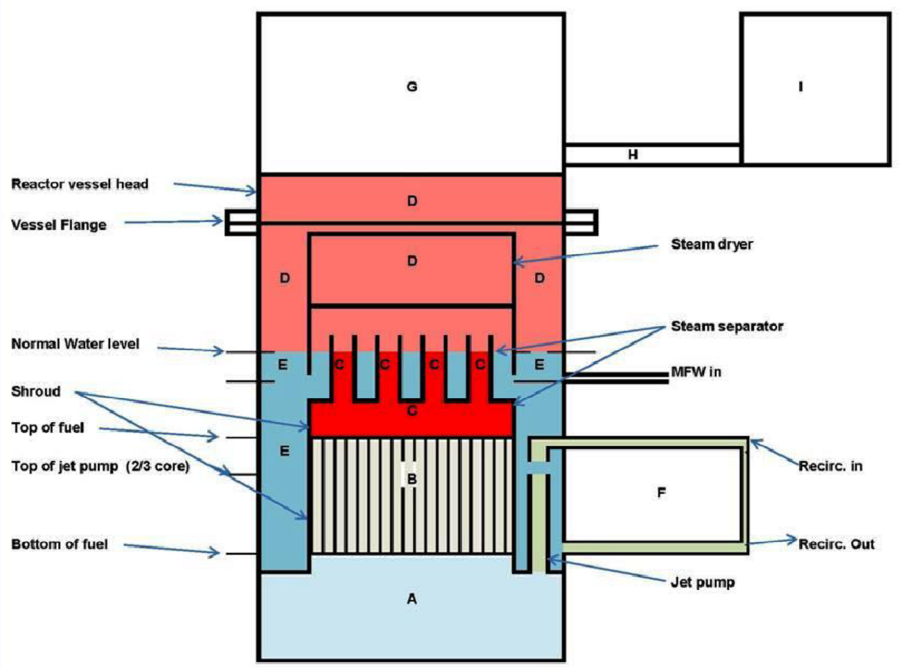
Figure 2-4. "New" ET Models for Davis Besse Plant

Volumes of water	Location			Volume (cubic ft)	Input used in calculation	Input percent used	Volume modeled (cubic ft)	Volume to boil-off (cubic ft)
A	Below fuel in reactor vessel			1050	1	100	1050	
B	Between top and bottom of fuel			1114	1	100	1114	
C	HL midplane to top of fuel			1233	1	100	1233	1233
D	HL midplane to RV flange			2256	1	0.85	19	19
E	Refueling cavity			40000	0		0	0
F	Fuel transfer canal			1000	0		0	0
G	Spent fuel pool			2000	0		0	0
H	Pressurizer			1500	0		0	0
I	All SGs			4000	0		0	0
	Total Volume =			51989			3416	1252
							V1	V2
Inputs								
		MWt	**BTU/hr**			to midplane of fuel	V3	1809
Reactor thermal power		3250	1.11E+10			to bottom of fuel	V4	2366
Months of power operation		18						
Initial water temperature (F)		100						
RCS pressure		atmospheric						
Preliminary calculations:								
							V3	**V4**
W1	Pounds of water to to be heated from starting bulk temperature to 212F				211803	lbs		
W2	Pounds of water to be boiled at 212 F			(also W3 and W4)	77635	lbs	112169	146703
ΔT	# of degrees F from initial water temperature to 212F				112	F		
E(heatup)	BTUs needed to heat up W1 by ΔT				2.372E+07	BTU		
E(boil)	BTUs needed to boil W2 at the given RCS pressure				7.533E+07	BTU	1.088E+08	1.423E+08
E(total)	Total decay heat needed to heat and boil water as calculated above				9.905E+07	BTU	1.326E+08	1.661E+08
1ftV	Volume of water in 1 ft of core height				80	ft^3		
1ftlb	pounds of water in 1 ft core height				4933	lbs		

Figure 2-5. Worksheet from the SD Core Uncovery Calculator

Schematic diagram of volumes of water modeled for a BWR

Scenario 3 — Loss of shutdown cooling (or loss of decay heat removal; or loss of RHR); No loss of inventory.



	Height inches
Top of water when cavity is full	480
Top of RV	480
Reactor vessel flange	390
Bottom of main steam line	
Normal water level	199
Low level trip (RHR SDC isolates)	175
Top of fuel	0
Top of jet pump 2/3 fuel	-48
Midplane of fuel	-72
Bottom of fuel	-144
Bottom of RV	-352

						Top of the fuel		Midplane of the fuel		Bottom of the fuel	
Volumes of water	Location	Volume (cubic ft)	Input used in calculation	Input percent used	Volume modeled (cubic ft)	Volume to heat (cubic ft)	Volume to boil-off (cubic ft)	Volume to heat (cubic ft)	Volume to boil-off (cubic ft)	Volume to heat (cubic ft)	Volume to boil-off (cubic ft)
A	Lower Plenum	2844	1	100	2844	2844		2844		2844	
B	Core	1525	1	100	1525	1525		1525	763	1525	1525
C	Upper plenum and separator	926	1	100	926	926	926	926	926	926	926
D	Dome (above normal water level)	5266	0		0						
E	Downcomer region	4533	1	50	2267	2267	2267	3400	3400	4533	4533
F	Recirc loops and jet pumps	1236			0						
G	Refueling cavity	40000			0						
H	Fuel transfer canal	1000			0						
I	Spent fuel pool	2000			0						
		59,330	Total Volume =		7562	7562	3193	8695	5088	9828	6984
					V0	V1h	V1b	V2h	V2b	V3h	V3b

Inputs	MWt	BTU/hr
Reactor thermal power	3250	1.11E+10
Months of power operation	18	
Initial water temperature (F)	100	
RCS pressure	atmospheric	

Preliminary calculations:				V1h	V1b	V2h	V2b	V3h	V3b
W	Pounds of water in the volumes to be heated up or boiled	lbs		468813	197935	539075	315472	609336	433008
ΔT	# of degrees F from initial water temperature to 212F	F	112						
E(heatup)	BTUs needed to heat up W by ΔT	BTU		5.25E+07		6.04E+07		6.82E+07	
E(boil off)	BTUs needed to boil off W at the given RCS pressure	BTU			1.92E+08		3.06E+08		4.20E+08

Figure 2-6. Worksheet from the SD Core Uncovery Calculator

Calculations for time to boil and time to uncover fuel:

Days after reactor trip	Decay heat Fraction P(to+t)/Po	Decay heat (MWt)	Decay Heat (BTU/Hr)	# of hours to reach boiling		# of hours from boiling to top of fuel		total # of hours to top of fuel	additional minutes to boil 1 ft below top of fuel	total # of hours to fuel midplane	total # of hours to bottom of fuel
3	4.71E-03	1.53E+01	5.22E+07	0.45	+	1.44	=	1.90	6	2.54	3.18
4	4.25E-03	1.38E+01	4.71E+07	0.50	+	1.60	=	2.10	6	2.81	3.53
5	3.91E-03	1.27E+01	4.34E+07	0.55	+	1.74	=	2.28	7	3.06	3.83
6	3.65E-03	1.19E+01	4.04E+07	0.59	+	1.86	=	2.45	7	3.28	4.11
7	3.43E-03	1.12E+01	3.80E+07	0.62	+	1.98	=	2.60	8	3.48	4.36
8	3.25E-03	1.06E+01	3.60E+07	0.66	+	2.09	=	2.75	8	3.68	4.61
9	3.09E-03	1.01E+01	3.43E+07	0.69	+	2.19	=	2.89	8	3.86	4.84
10	2.96E-03	9.62E+00	3.28E+07	0.72	+	2.30	=	3.02	9	4.04	5.06
11	2.84E-03	9.23E+00	3.15E+07	0.75	+	2.39	=	3.15	9	4.21	5.27
12	2.73E-03	8.88E+00	3.03E+07	0.78	+	2.49	=	3.27	9	4.37	5.48
13	2.64E-03	8.57E+00	2.92E+07	0.81	+	2.58	=	3.39	10	4.53	5.68
14	2.55E-03	8.28E+00	2.83E+07	0.84	+	2.67	=	3.51	10	4.69	5.88
15	2.47E-03	8.02E+00	2.74E+07	0.87	+	2.75	=	3.62	10	4.84	6.07
16	2.39E-03	7.78E+00	2.65E+07	0.89	+	2.84	=	3.73	11	4.99	6.26
17	2.33E-03	7.56E+00	2.58E+07	0.92	+	2.92	=	3.84	11	5.14	6.44
18	2.26E-03	7.35E+00	2.51E+07	0.95	+	3.00	=	3.95	11	5.29	6.62
19	2.20E-03	7.16E+00	2.44E+07	0.97	+	3.08	=	4.06	12	5.43	6.80
20	2.15E-03	6.98E+00	2.38E+07	1.00	+	3.16	=	4.16	12	5.57	6.98
21	2.09E-03	6.81E+00	2.32E+07	1.02	+	3.24	=	4.26	12	5.71	7.15
22	2.05E-03	6.65E+00	2.27E+07	1.05	+	3.32	=	4.37	13	5.84	7.32
23	2.00E-03	6.50E+00	2.22E+07	1.07	+	3.40	=	4.47	13	5.98	7.49
24	1.96E-03	6.36E+00	2.17E+07	1.09	+	3.47	=	4.57	13	6.11	7.66
25	1.91E-03	6.22E+00	2.12E+07	1.12	+	3.55	=	4.67	14	6.25	7.82
26	1.87E-03	6.09E+00	2.08E+07	1.14	+	3.62	=	4.77	14	6.38	7.99
27	1.84E-03	5.97E+00	2.04E+07	1.16	+	3.70	=	4.86	14	6.51	8.15
28	1.80E-03	5.85E+00	2.00E+07	1.19	+	3.77	=	4.96	14	6.64	8.32
29	1.77E-03	5.74E+00	1.96E+07	1.21	+	3.85	=	5.06	15	6.77	8.48
30	1.73E-03	5.63E+00	1.92E+07	1.23	+	3.92	=	5.15	15	6.90	8.64
45	1.37E-03	4.44E+00	1.52E+07	1.57	+	4.97	=	6.54	19	8.75	10.96
60	1.13E-03	3.68E+00	1.26E+07	1.89	+	5.99	=	7.88	23	10.54	13.21
90	8.47E-04	2.75E+00	9.39E+06	2.53	+	8.02	=	10.54	31	14.11	17.68
10	2.96E-03	9.62E+00	3.28E+07	0.72	+	2.30	=	3.02	9	4.04	5.06

Figure 2-7. Worksheet from the SD Core Uncovery Calculator

2.8 Additional Considerations for Shutdown Risk Analysis

In addition to the important aspects of shutdown risk mentioned above, several issues, unique to shutdown operations, should be addressed when performing a risk analysis. For additional guidance on these SD-related considerations, refer to Section 8. These considerations are provided in Section 8 to give the analyst a list of frequently encountered pitfalls in developing shutdown risk models. Some of these considerations are highlighted below.

- ***Operator Actions.*** Operator actions generally contribute significantly to the most risk important SD scenarios. Multiple operator actions may be credited in a scenario, with potential interaction (dependencies) among them. Appendix B discusses the treatment of operator actions in SD scenarios.

- ***Testing and maintenance during forced and planned outages.*** If the scenario is during a forced outage, the test and maintenance (T/M) unavailabilities may be nominal (as modeled in the at-power model). However, if the scenario is during a planned outage, plant procedures or administrative controls may preclude scheduled test and maintenance on key equipment trains (such as emergency diesel generators); on the other hand, random failures may occur and lead to unscheduled maintenance.

  In some SD scenarios, multiple trains of the same system may be out of service due to scheduled maintenance. This may not be allowed during power operation. These aspects of shutdown conditions should be considered on a case by case basis and, if necessary, should be used to justify modifying the T/M unavailabilities for the case.

- ***Time between shutdown and event or plant condition.*** Another important aspect in characterizing shutdown risk is the decay heat level. The time between the plant shutdown and occurrence of an event or plant condition determines the decay heat rate applicable to the scenario and may affect the operator action time windows, and even equipment success criteria. To account for the various levels of decay heat (DH), four time windows were defined in terms of time after reactor shutdown. These four DH time windows are defined in Table 2-1 and discussed in Section 8.9.

Table 2-1. Decay Heat Time Window Definition[2]

Condition	DH Time Window 1	DH Time Window 2	DH Time Window 3	DH Time Window 4
Time following shutdown	< 75 h	Between 75 h and 240 h	Between 240 h and 768 h	> 768 h (32 days)
Percent of full power	0.54	0.41	0.29	0.20

2.9 Example CCDPs and CDPs

As shown below, a set of example CCDPs and CDPs is provided for plant SD modes modeled by template event trees in the current SPAR-SD models for a PWR.

Shutdown Scenario CCDPs

Mode/POS	LORHR	LOOP	LOI	OD*	
M4	1.3E-05	2.3E-06	3.3E-05		PWR Mode 4
M5	1.0E-05	2.3E-06	3.2E-05		PWR Mode 5
ML	1.4E-04	1.8E-04	1.5E-03	2.5E-03	PWR Mode 5 RCS Open
M6			1.1E-05		PWR Mode 6 (Refueling)

When the model is complete, the CDP per hour for each POS can be calculated and recorded in a table such as the one below.

POS CDPs (per hour in that mode)

Mode/POS	LORHR	LOOP	LOI	OD*	
M4	4.1E-11	9.3E-12	2.8E-11		PWR Mode 4
M5	3.3E-11	9.3E-12	2.7E-11		PWR Mode 5
ML	4.6E-10	7.5E-10	1.3E-09	4.4E-05	PWR Mode 5 RCS Open
M6			9.3E-12		PWR Mode 6 (Refueling)

* *Per mid-loop operation (demand basis)*

Loss of inventory (LOI) event
Loss of RHR (LORHR) cooling event
Loss of offsite power (LOOP) event
Over-drain (OD) event during mid-loop operation

[2] Time Window definitions are taken from NUREG/CR 6144 and are given in SPAR-SD model reports of the earlier SPAR-SD models, such as Davis-Besse.

2.10 References

2-1. Idaho National Laboratory, “SAPHIRE Users Group,” https://saphire.inl.gov/, User Area Accessible to NRC-Authorized Account Holders Only.

2-2. Shutdown SPAR Model Library, Internal NRC ADAMS Accession Number ML070220201, Internal ADAMS Accessible to NRC-Authorized Account Holders Only

2-3 Shutdown Core Uncovery Calculator, Internal NRC ADAMS Accession Numbers: ML101880081 (Calculator), Internal ADAMS Accessible to NRC-Authorized Account Holders Only.

3.0 Scenario Definition and Quantification

Shutdown scenarios can be defined and their CCDPs (for event analysis) or CDPs (for plant condition analysis) can be calculated using a SPAR-SD model. In this Handbook, it is assumed that there may or may not be a plant-specific SPAR-SD model available to the analysts.

At this time, there are only a few SPAR-SD models available. The analyst may need to construct the needed SD scenarios using portions of model logic from the at-power model, SD event tree templates, and the SD HEP library mentioned in Section 2, and illustrated in Figure 2-1. The system fault trees can be borrowed from the existing at-power model and modified as necessary to map the realistic SD conditions.

3.1 Scenario Types

In this document, the following cases are discussed and examples are provided:

- Event analysis (calculate a CCDP)
- Plant condition analysis involving one POS (calculate CDP).
- Plant condition analysis involving multiple POSs (calculate CDP).
- Special cases (no predefined POS available for the SD scenario of interest).

For plant condition cases, CDP of the condition case is discussed; CDP of the based case could be calculated by removing the condition from the model. CDP of the base case can be separately calculated and subtracted from the CDP of the condition case to calculate the scenario delta-CDP, when needed. If the CDP of the base case is judged not to affect the scenario delta-CDP classification, then base case calculation need not be performed.

It is assumed that the analyst will need to construct a SPAR-SD model containing a minimum set of needed POSs and initiating events to address the issue.

3.2 Process Outline

The following process is provided to model SD scenarios and quantify their CDFs:

- Identify if the issue is an event analysis or a plant condition analysis.

- Identify the shutdown state(s), mode(s), or POS(s) the issue applies to. In some cases, an issue (such as a plant condition) may not apply to as few of the POSs; thus the remaining POSs need not be considered. See Figure 3-1 for definition of a detailed set of POSs for a PWR.

- For an event analysis, identify the following (see Section 4 for examples):

- Initiating event (see Table 3-1);
- Failed components/unavailable components (if any);
- Operator actions that may need to be adjusted;
- Time since the plant was last shutdown; and
- Whether the event is during a forced outage or a planned outage.

Table 3-1. PWR SPAR SD Model Initiating Events[3]

SPAR Name	Description[4]
IESD-LORHR	Loss of Decay Heat Removal Capability [Other Than Residual Heat Removal (RHR) Loop Isolation]
IESD-ISOL	RHR Loop Isolation
IESD-LOOP	LOOP
IESD-LOAC	Loss of Operating an Alternate Current (AC) Division
IESD-LOI	Loss of Inventory Due to Loss-of-Coolant Accident (LOCA) or Recoverable Diversion of RCS Coolant
IESD-LOLC	Loss of Level Control at Reduced Inventory
IESD-OD	Loss of Inventory at Reduced Inventory Due to Over-Draining (Demand-Related Rate)[5]

- For a plant condition analysis, identify the following:

  - POS (or multiple POSs) involved;

    (Identify only the minimum number of POSs and initiating events necessary for the issue, since most likely, new ETs need to be constructed.)

  - Time spent in each in each POS;
  - Failed components/unavailable components (if any);
  - Operator actions that may need to be adjusted;
  - Time since the plant was last shutdown;
  - Whether the condition is during a forced outage or a planned outage; and
  - If PWR and mid-loop operations are involved, the number of times the mid-loop state is entered.

  See Section 5 for examples with one POS; see Section 6 for examples with multiple POSs.

- If available, use a plant-specific SPAR-SD model. The most likely case is that such a model will not be available. In that case, construct (or import from the ET library) the minimum number of ETs to carry out the analysis

[3] Taken from a SPAR-SD model in Reference 1-3.

[4] Rates are given per shutdown year (except for IESD OD).

[5] IESD-OD is the demand-related loss of inventory caused by the operator over-draining the RCS with the intent of reducing RCS level to mid-loop (or reduced inventory conditions). This SPAR value is per demand, and does not have time-based units.

- Quantify the CCDP or CDP of the scenario by solving for the sequences of only those ETs that are involved in the scenario.

- Examine the cutsets to make sure that they reflect the intended scenario. Especially check operator action HEPs and validity of cutsets containing operator actions. Check for dependencies among operator actions. Modify as needed to obtain a proper estimate of risk for cutsets involving multiple operator actions. In the newer models built by MMG, dependencies are introduced by SAPHIRE basic event replacement rules (contained in recovery rules file); this is discussed in Appendix B.

In the SPAR-SD models, the SD scenario is assumed to occur at some “nominal” time after the reactor shutdown. If the event/plant condition applies to an earlier POS during the shutdown, operator time windows may be shorter (due to higher decay heat) than the same event/plant condition applying to a later POS (say after refueling is completed). The POS occurring early or late after shutdown may affect the operator action success criteria (by affecting the available time window), and even may affect system success criteria. Nominal means that the POS occurs in the most likely DH time window (See Section 8.9 and Table 2-1) expected for that POS. For example hot shutdown and hot standby will be in DH time window 1; cold shutdown and refueling will be in DH time window 2. In forced outages for repairs, cold shutdown may slide into DH time windows 3 and 4. A 20- to 30-day refueling outage will span DH time windows 1, 2 and 3, but will not go into DH time window 4.

The event tree of Figure 3-1 is used to help an analyst to identify POSs of interest. Twelve POS’s for various PWR shutdown states are defined by Figure 3-1.

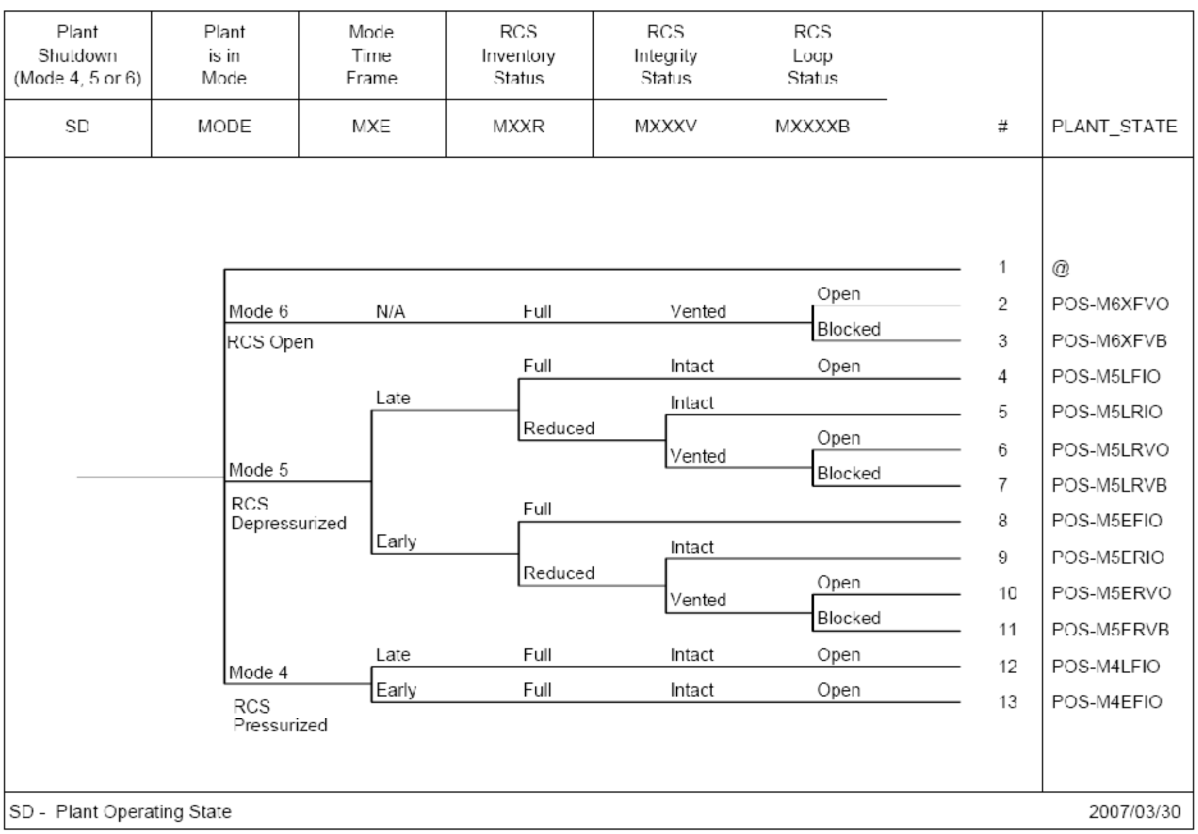


Figure 3-1. Example Definition of Plant Operating States (POS)

3. Scenario Definition and Quantification

The next four sections discuss examples for illustrative purposes; the values used in the examples are for illustration only.

4.0 Shutdown Event Analysis

This section provides examples of how to quantify the CCDP of an event that occurs in shutdown, and that can be modeled by one of the existing SPAR-SD models. These examples are:

- Example 4.1a: A loss of RHR event occurs during refueling mode; event importance is calculated by using the Davis-Besse SPAR-SD model.

- Example 4.1b: A loss of RHR event occurs during refueling mode; event importance is calculated by using the Seabrook SPAR-SD model.

- Example 4.2: A LOOP event due to hurricane occurs during Mode 4; event importance is calculated by using the Davis-Besse SPAR-SD model.

In a shutdown event analysis, the POS is fixed and the initiating event has already occurred; CCDP of the event is to be calculated. The analyst must set the initiating event (IE) frequency to 1.0 for the event tree that is used to model the relevant POS and IE. The event tree sequences are then solved to calculate the scenario CCDP.

The analyst must exercise caution when using an existing SPAR-SD event tree model to ensure that the model is actually applicable to the scenario in question. When an existing SPAR-SD event tree is observed to be not applicable to the scenario, the analyst needs to create a SD event tree or modify an existing SD event tree. Assumptions are often made about the initiating event (failure mechanism, recoverability), success criteria, system availability and lineup, etc. in the existing event tree models. It is not feasible to model all possible scenarios in the existing SD models. The analyst must review the model and model documentation to ensure the applicability to the event that is to be assessed.

4.1 Examples 4.1a and 4.1b

While the plant is in Mode 6, RCS full and vented and RCS loops open, a loss of RHR event occurs. What is the CCDP?

- ***4.1a. Using the Davis-Besse SPAR-SD Model (pre-MMG model).*** The results of process steps 1, 2, and 3 described in Section 2.2 apply to this case; the results of these steps are summarized in the following paragraph.

  This is an event importance analysis. This plant mode is represented by POS-M6XFVO (see Table A-2 for these POS definitions) in the Davis-Besse shutdown model. The initiating event is IESD-LORHR. The existing model assumptions with respect to equipment availability and operator actions are assumed to apply. No other equipment is affected in this scenario. The plant has been shutdown for 18 days, before this event has occurred.

Process step 4 does not apply since this case is not a plant condition. For step 5, a plant-specific SPAR-SD model is available and can be used. Step 6 is discussed in the next paragraph.

To quantify the CCDP of this case, make a change set containing eight basic events; six basic events are set to FALSE; one set to TRUE; and one is set to 1.0, as shown below.

Event	Probability
IESD-ISOL	FALSE
IESD-LOAC	FALSE
IESD-LOI	FALSE
IESD-LOLC	FALSE
IESD-LOOP	FALSE
IESD-LORHR	TRUE
IESD-OD	FALSE
POS-M6XFVO	1.0

In this case, the POS basic event is set to 1.0; the loss of RHR initiating event has occurred and its basic event is set to TRUE; the remaining initiating events for the same POS are set to FALSE. Note that in this model, and in all pre-MMG SPAR-SD models, it is not possible to select and run a single initiating event tree for a POS; the whole POS CCDP must be quantified, because the underlying ET rules are determined by the POS. On the other hand, in the post-MMG SPAR-SD models (see the next case 3.1b); one or more initiating events for a plant mode or multiple plant modes can be selected and quantified, since each ET includes its own underlying rules.

Select the change set; generate. Then select all sequences for the POS-M6XFVO and solve with cutoff probability of 1E-12. The resulting CCDP is 1.0E-05, with 3653 cutsets.

Per step 7 of the process, examine cutsets to establish that they make sense and contain all intended failures.

- ***4.1b. Using the Seabrook SPAR-SD Model (made by using MMG model).*** The same process as Example 3.1a is followed.

  This plant mode is represented by the event tree M6-LORHR in the Seabrook shutdown model. The initiating event is IE-M6-LORHR. The existing model assumptions with respect to equipment availability and operator actions are assumed to apply. No other equipment is affected in this scenario. The plant has been shutdown for 18 days, before this event has occurred.

  Note that this is a post-MMG model. Thus a single SD event tree can be quantified without involving other event trees for the same SD mode. This quantification is identical to what would have been done for an event analysis for power operations.

  To quantify the CCDP of this case, make a change set containing one basic event, namely the initiating event frequency of IE-M6-LORHR set to TRUE. Select the change set; generate. Then select all sequences for M6-LORHR and solve with cutoff probability of 1E-13. The resulting CCDP is 3.3E-03, with 536 cutsets. Note that the ET success criteria in this model require recovery of RHR in the long term to avoid core damage.

Examine cutsets to establish that they make sense and contain all intended failures.

4.2 Example 4.2

- ***Description of the case.***[6] In the late evening hours of September 5th, the unit was shutdown in Mode 4 as the effects of Hurricane J, a Category 3 hurricane on the Saffir-Simpson scale, were experienced at the site. Earlier that day the unit was taken off-line, as required by the emergency plan implementing procedures, prior to the onset of hurricane force winds at the site.

  The unit was removed from service at 1100 hours on September 5th. At 2356 hours the same day, power to the east switchyard bus was lost causing a complete loss of offsite power. The emergency diesel generators started in response the LOOP conditions and safe shutdown loads were sequenced onto the unit's safety busses.

- ***Scenario Setup.*** Davis-Besse SPAR-SD model was used to illustrate quantification of event importance for this case. The plant was in POS-M4EFIO; IESD-LOOP event occurred; plant was in mode 4 thirteen hours after the shutdown. This is a forced outage scenario.

  The following offsite power recovery distribution was created for particular scenario. Note that the basic events for this recovery already exist in the SPAR model and contain nominal recovery probabilities based on average actuarial behavior of the fleet of domestic nuclear power plants. Not all recovery basic events may be actually utilized in a given SPAR model. The probability distribution used for this case recognizes the following:

  - Offsite recovery during the first hour is not credited due to high hurricane winds at the site.
  - During the second hour a 50% chance of recovery was modeled.
  - During the third hour, a high probability (95%) of offsite recovery was modeled.
  - After the third hour, the recovery was modeled to be highly likely to occur (99.5%) without distinguishing when it actually occurs.

  This recovery failure distribution can be assigned to the applicable basic events in the model as follows:

Event	Description	Probability
OEP-XHE-XL-NR01H	OPERATOR FAILS TO RECOVER OFFSITE POWER IN 1 HOUR	1
OEP-XHE-XL-NR90M	OPERATOR FAILS TO RECOVER OFFSITE POWER IN 90 MINUTES	Not used

[6] This event happened at a different site; it is used here for illustration purposes only.

Event	Description	Probability
OEP-XHE-XL-NR02H	OPERATOR FAILS TO RECOVER OFFSITE POWER IN 2 HOURS	0.5
OEP-XHE-NOREC-BD	OPERATOR FAILS TO RECOVER OFFSITE POWER BEFORE BATTERY DEPLETION	0.5
OEP-XHE-XL-NR03H	OPERATOR FAILS TO RECOVER OFFSITE POWER IN 3 HOURS	0.05
OEP-XHE-XL-NR04H	OPERATOR FAILS TO RECOVER OFFSITE POWER IN 4 HOURS	0.005
OEP-XHE-XL-NR05H	OPERATOR FAILS TO RECOVER OFFSITE POWER IN 5 HOURS	0.005
OEP-XHE-XL-NR06H	OPERATOR FAILS TO RECOVER OFFSITE POWER IN 6 HOURS	0.005
OEP-XHE-XL-NR07H	OPERATOR FAILS TO RECOVER OFFSITE POWER IN 7 HOURS	0.005
OEP-XHE-XL-NR08H	OPERATOR FAILS TO RECOVER OFFSITE POWER IN 8 HOURS	0.005

However, an examination of the SD LOOP model shows that the model credits only a single AC power recovery action at 6 hours for this SD ET follows:

OSP-SD-06HRS with failure probability of 5.7E-02. This value is replaced with 5.0E-03, as given in the above data.

Since this is a pre-MMG SPAR-SD model, to quantify the CCDP of this case, make a change set containing nine basic events; six basic events corresponding to other initiating events are set to FALSE; two are set to 1.0 (POS and the actual initiating event that has occurred); and one is set to 5.0E-03 (the AC power recovery basic event affected by the case), as shown below.

Event	Probability
IESD-ISOL	FALSE
IESD-LOAC	FALSE
IESD-LOI	FALSE
IESD-LOLC	FALSE
IESD-LOOP	1.0
IESD-LORHR	FALSE
IESD-OD	FALSE
OSP-SD-06HRS	5.00E-03
POS-M4EFIO	1.0

Select the change set; generate. Then select all sequences for the POS-M4EFIO and solve with cutoff probability of 1E-12. The resulting CCDP is 8.176E-5, with 44954 cutsets.

Examine top cutsets to establish that they make sense and contain all intended failures.

Note that this model does not consider battery depletion, and early problems with auxiliary feedwater (AFW) turbine-driven pump (TDP) control. Another scenario approach, which uses a modified at-power LOOP event tree for modeling this scenario, *may be considered. In that case, the at-power LOOP event tree can be modified to remove anticipated transient without scram (ATWS) and reactor coolant pump (RCP) LOCA issues; and quantified with a more detailed AC power recovery distribution.*

5.0 Shutdown Condition Analysis – 1 POS

In this section, examples of plant condition analysis for one POS and for multiple POSs are given. The examples calculate CDP for a time spent in a POS for a specified number of hours [duration time (DT)] with the plant condition.

5.1 Example 5.1

Plant spends 200 hrs in POS 12 (POS-M6XFVO; Mode 6, RCS Full and Vented, Loops Open) with AFW TDP 11 and DG 11 out of service. What is the total CDP during this shutdown?

The POS fraction is 200/8760 = 0.022831.

To quantify the CDP of this case, make a change set containing the following basic events:

Event	Probability
AFW-TDP-TM-11	TRUE
EPS-DGN-TM-DG11	TRUE
POS-M6XFVO	2.283E-02

Select the change set; generate. Then select all sequences for the POS-M6XFVO and solve with cutoff probability of 1E-12. The resulting CDP is 3.374E-6, with 7642 cutsets.

Examine top cutsets to establish that they make sense and contain all intended failures. If needed provide recovery actions or additional credit.

5.2 Example 5.2

While early in mode 5, with RCS reduced, vented and loops open (POS-M5ERVO), the plant spends 30 hours; what is the CDP? During this time the RCS level was drained to mid-loop level once.

The POS fraction is 30/8760 = 0.003425.

This POS is one of the two mid-loop modes where the demand based IESD-OD initiating event applies. The value of IESD-OD in the model is 0.018, which implies that, every time this mid-loop POS is exercised (regardless of its duration), there is a 1.8% chance that over-draining would occur.

The initiating event “frequency” (challenge) of this event does not depend on how long is the POS DT, but depends on how many times (N) the mid-loop is exercised. Since the POS fraction is DT related, the initiating event frequency of IESD-OD must be adjusted so that the product of POS fraction times the IESD-OD is N times 0.018:

5. Shutdown Condition Analysis – 1 POS

DT / 8760 *(frequency of IESD) = N * 0.018

Thus, the frequency of IESD = N * 0.018 *8760 / DT

In this case, N=1, and DT = 30

Frequency of IESD = 5.256.

This is the value that must be assigned to IESD-OD in the change set.

To quantify the CDP of this case, make a change set containing the following basic events:

Event	Probability
IESD-OD	5.256E+00
POS-M5ERVO	3.425E-03

Select the change set; generate. Then select all sequences for the POS-M5ERVO and solve with cutoff probability of 1E-12. The resulting CDP is 6.793E-7, with 3592 cutsets.

Examine top cutsets to establish that they make sense and contain all intended failures. If needed provide recovery actions or additional credit.

6.0 Shutdown Condition Analysis – Multiple POSs

If there is a plant-specific SPAR-SD model, then this case can be treated as a sum of multiple single-POS cases. CDPs for each POS can be calculated and added. This is illustrated in the example shown in Tables 5-1a, and 5-1b for a PWR case. This case is for illustration purposes only.

In this case, plant is placed in cold shutdown for forced outage for tech-spec related minor repairs. During cold shut down, it is discovered that one high-head safety injection (HHSI) pump was inoperable for the last 614 hours. Five hundred hours were at-power; the remaining 114 hours were at different shutdown states. The base case CDPs for at-power and shutdown states are already calculated and given in the SPAR-SD model report as:

Mode	CDP (for 8760 hours)
Power Operation	1.8E-05
M4	5.5E-06
M5	5.8E-06
MR	1.3E-03
ML	1.8E-03
M6	1.5E-04

The hot standby CDP can be approximated by the at-power CDP since the same plant configuration (except for reactor trip) exists. This approximation may be slightly conservative. The plant response to events at hot standby is the same as the one for at-power operation. If needed, this assumption can be modified to remove events like ATWS, Transients, etc., which may not be applicable to the mode being modeled. In the current case, this correction is not deemed to be a contributing factor.

Table 6-1a shows the calculation of the base plant CDP for the 614 hour-time window in multiple states. Then, the SPAR-SD model is run with one HHSI pump set to failure and new CDPs are calculated. These CDPs are used in Table 6.1b to calculate the plant condition CDP. Finally, the plant condition importance is calculated as the difference between the plant condition CDP and the base CDP:

Plant Condition Importance = Plant Condition Case CDP – Base Case CDP

= 1.23E-06 - 1.11E-06 = 1.2E-07

Table 6-2 shows an example table that can be used for a similar calculation for a BWR. An application to a BWR is shown in Table 6-3. Note that in this case, only the plant condition CDP is calculated, but not the base case CDP, since the plant condition CDP is already less than 1E-06.

Table 6-1a. Plant Condition Importance Calculation – PWR Base Case

Case Name Example PWR case with multiple shutdown states and at-power state involved. Base case CDP calculation.

Case Description Plant is placed in cold shutdown for forced outage for TS-related minor repairs. During cold shut down, it is discovered that one HHSI pump was inoperable for the last 614 hour time period. 500 hours were at power. Estimate the event importance for this plant condition.

Plant Operating State	TS Mode	TS Mode Description	POS Description	DH Time Window	Hours in POS	CDF (per yr) or CCDP	POS CDP	Additional Equipment Unavailable
P1	1	Power Operation	Low power and reactor shutdown	N/A	500	1.80E-05	1.03E-06	
P2	3	Hot Standby	Cooldown with Steam Generators (SGs) from operating temperature to 345°F	1	4	1.80E-05	8.22E-09	
P3	4	Hot Shutdown	Cooldown with RHR from 345°F to 200°F)	1	35	5.50E-06	2.20E-08	
P4	5	Cold Shutdown	Cooldown with RHR (below ~200°F)	1-2	75	5.80E-06	4.97E-08	
P5	5	Cold Shutdown	Draining RCS to mid-loop					
P6	5	Cold Shutdown	Mid-loop operation					
P7	5	Cold Shutdown	Fill for refueling					
P8	6	Refueling	Refueling					
P9	5	Cold Shutdown	Draining RCS to mid-loop after refueling					
P10	5	Cold Shutdown	Mid-loop operations after refueling					
P11	5	Cold Shutdown	Refilling RCS					
P12	5	Cold Shutdown	RCS heat-up solid and draw bubble					
P13	4	Hot Shutdown	RCS heat-up to 350°F					
P14	2	Startup	RCS heat-up with SGs available (above 350°F)					
P15	1	Power Operation	Startup and low power operations					
			Base Case CDP =				**1.11E-06**	

Table 6-1b. Plant Condition Importance Calculation – PWR Condition Case

Case Name Example PWR case with multiple shutdown states and at-power state involved. Plant condition CDP calculation.

Case Description Plant is placed in cold shutdown for forced outage for tech-spec related minor repairs. During cold shut down, it is discovered that one HHSI pump was inoperable for the last 614 hour time period. 500 hours were at power. Estimate event importance for this plant condition.

Plant Operating State	TS Mode	TS Mode Description	POS Description	DH Time Window	Hours in POS	CDF (per yr) or CCDP	POS CDP	Additional Equipment Unavailable
P1	1	Power Operation	Low power and reactor shutdown	N/A	500	2.00E-05	1.03E-06	One HHSI pump out of service
P2	3	Hot Standby	Cooldown with SGs from operating temperature to 345°F	1	4	2.00E-05	8.22E-09	One HHSI pump out of service
P3	4	Hot Shutdown	Cooldown with RHR from 345°F to 200°F)	1	35	6.10E-06	2.20E-08	One HHSI pump out of service
P4	5	Cold Shutdown	Cooldown with RHR (below ~200°F)	1-2	75	6.50E-06	4.97E-08	One HHSI pump out of service
P5	5	Cold Shutdown	Draining RCS to mid-loop					
P6	5	Cold Shutdown	Mid-loop operation					
P7	5	Cold Shutdown	Fill for refueling					
P8	6	Refueling	Refueling					
P9	5	Cold Shutdown	Draining RCS to mid-loop after refueling					
P10	5	Cold Shutdown	Mid-loop operations after refueling					
P11	5	Cold Shutdown	Refilling RCS					
P12	5	Cold Shutdown	RCS heat-up solid and draw bubble					
P13	4	Hot Shutdown	RCS heat-up to 350°F					
P14	2	Startup	RCS heat-up with SGs available (above 350°F)					
P15	1	Power Operation	Startup and low power operations					
			Plant Condition Case CDP =				**1.23E-06**	

DH Time Window	**Percent of Full power**	**Time Following Shutdown (in hours)**
1	0.54	T<75 (3 days)
2	0.41	75=<T<240 (10 days)
3	0.29	240=<T<768 (32 days)
4	0.20	768<=T (32 days)

Table 6-2. Plant Condition Importance Calculation Table for a BWR

Case Name

Case Description

Plant Operating State	TS Mode	TS Mode Description	POS Description	DH Time Wind ow	Hours in POS	CDF (per yr) or CCDP	POS CDP	Additional Equipment Unavailable
B1	1	Power Operations: Mode Switch in Run, plant at any temperature						
B2	2	Startup: Mode Switch in Startup/Hot Standby, plant at any temperature	Hot Standby; T > 200 °F; early refueling					
B3	3	Hot shutdown: Mode Switch in Shutdown, plant temperature greater than 200°F,	Hot shutdown; T ≤ 200 °F; early refueling					
B4	4	Cold Shutdown: Mode Switch in Shutdown, plant temperature 200oF, or lower	Early refueling; RCS pressure low; RCS level normal					
B5	5	Refueling: Fuel in vessel with head de-tensioned or removed, Mode Switch in Shutdown or Refueling	Early refueling [reactor pressure vessel (RPV) head off]; RCS pressure low; RCS level normal					
B6	5	Refueling	Early refueling(RPV head off); RCS pressure low; RCS level at steam line					
B7	5	Refueling	Refueling(RPV head off); RCS pressure low; upper pool filled					
B8	5	Refueling	Late refueling(RPV head off); RCS pressure low; RCS level at steam line					
B9	5	Refueling	Late refueling(RPV head off); RCS pressure low; RCS level normal					
B10	4	Cold Shutdown	Late refueling; RCS pressure low; RCS level normal					
B11	4	Cold Shutdown	Late refueling; RCS pressure high (hydrostatic test); RCS level normal					
B12	3	Hot Shutdown	Hot Shutdown T > 200 °F; late					
B13	2	Startup: Mode Switch in Startup/Hot Standby, plant at any temperature	Startup					
			Total CDP =					

Table 6-3. Plant Condition Importance Calculation Table for a BWR

Case Name BWR plant-XOC loss of 4.16 kV Emergency Bus 1C due to ground fault in normally energized underground cable

Case Description Plant condition analysis with 4160 emergency VAC unavailable for 130 hours at shutdown conditions (due to TS requirements). See Note 1 for initiating events at shutdown considered.

Plant Operating State	TS Mode	TS Mode Description	POS Description	DH Time Window	Hours in POS	CDF (per yr) or CCDP	POS CDP	Additional Equipment Unavailable
B1	1	Power Operation	Power Operation (full or partial)					
B2	2	Hot Standby	Hot Standby, early refueling					
B3	3	Hot Shutdown	Hot Shutdown T > 200 °F; early refueling	1	75	4.18E-09	3.13E-07	4.16 kV Bus 1C
B4	4	Cold Shutdown	Cold Shutdown T ≤ 200 °F; early refueling	2	55	4.18E-09	2.30E-07	4.16 kV Bus 1C
B5	5	Refueling	Early Refueling; RCS pressure low; RCS level normal					
B6	5	Refueling	Early Refueling (RPV head off); RCS pressure low; RCS level normal					
B7	5	Refueling	Early Refueling (RPV head off); RCS pressure low; RCS level at steam line					
B8	5	Refueling	Refueling(RPV head off); RCS pressure low; upper pool filled					
B9	5	Refueling	Late Refueling(RPV head off); RCS pressure low; RCS level at steam line					
B10	4	Cold Shutdown	Cold Shutdown T ≤ 200 °F; late					
B11	4	Cold Shutdown	Hydro test; Cold shutdown late refueling					
B12	3	Hot Shutdown	Hot Shutdown T > 200 °F; late refueling					
B13	2	Startup	Startup					
			Total Condition CDP =		130		**5.43E-07**	

Note 1: During shutdown period, isolation condenser could be credited for decay heat removal, as modeled in the at-power operation in the SPAR models.

Plant Mode / Event Type	IE Frequency (per year)	Condition CDF (per year)	Condition CDF (per hr)
LOOP / IE-LOOP-SD	3.31E-02	2.96E-07	3.38E-11
Loss of Running RHR / IE-TRANS-SD	5.00E-06	4.02E-06	4.59E-10
Loss of DC Bus B / IE-LODCB-SD	2.50E-03	1.40E-07	1.60E-11
Loss of Intake Structure / IE-LOIS-SD	7.50E-03	3.05E-05	3.48E-09
Loss of SW / IE-LOSWS-SD	4.00E-04	1.63E-06	1.86E-10
			Total = 4.18E-09

Note 2: Base CDP is not calculated since the plant condition CDP is already less than 1E-06.

7.0 Cases Where No SPAR-SD Model Exists

7.1 Example Condition Analysis – Modify At-Power Model

If there is no SPAR-SD model, and it is not feasible to construct one in a short time period, then the analyst should focus on a minimum number of risk-relevant POSs and initiating events. An actual example of such an SDP Phase 3 analysis occurred in 2009 for a four-loop single unit PWR where the RHR pumps had a condition during Mode 2. This condition is determined to be limited to Modes 2 and 3 only and a short time window. The risk-significant initiating events for this condition were determined to be events generating a safety injection (SI) signal (mainly LOCAs of different sizes). The modeling was limited to Mode 2 with LOCA initiating events and the ETs from at-power mode were borrowed and simplified to assess the risk for a short time window of this condition. The condition importance (ΔCDP) was quantified.

7.2 Example Event Analysis – Create New ET

For SD events or plant conditions that may not have a readily available SD SPAR model, an issue-specific model would have to be developed. An example is the ASP analysis performed for an event that involved low-temperature over-pressure (LTOP) conditions. No ET model for that event existed and was previously created. The ET models created for this event are given in the ET data base. One of these ETs is shown in Figure 7-1 for illustrative purposes. Definition, assignment, and quantification of shutdown-specific operator actions in fault trees (FTs) are discussed further in Appendix B of this document.

The following process is provided in these cases:

- Identify whether the issue is an event analysis or a plant condition analysis.
- Identify the shutdown state(s), mode(s), or POS(s) the issue lends itself. See Figure 3-1 for definition of POSs for an example plant, such as Davis-Besse. (The Davis-Besse SPAR-SD model is built by generic ET templates. For a later SPAR-SD model built by MMG, see Seabrook MMG model.)
- For an event analysis, identify the following:
    - Initiating event;
    - POS;
    - Failed components / unavailable components (if any);
    - Operator actions that may need to be adjusted;
    - Time since the plant was last shutdown; and
    - Whether the event is during a forced outage or a planned outage.
- For a plant condition analysis, identify the following:

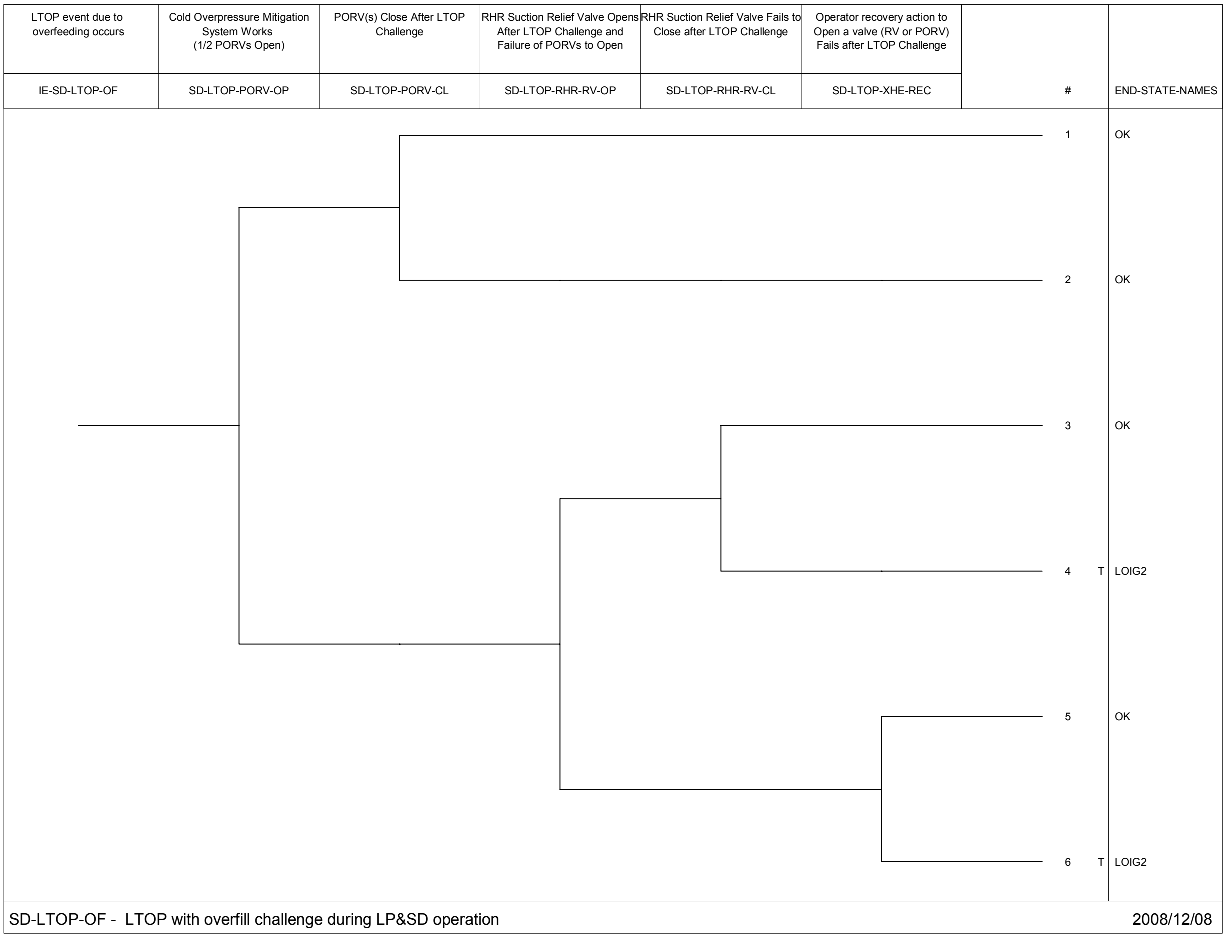


Figure 7-1. Example Event Tree for LTOP Event

- POS (or multiple POSs) involved; (Identify only the minimum number of POSs and initiating events necessary for the issue, since most likely, new ETs need to be constructed.)
- Time spent in each in each POS;
- Failed components / unavailable components (if any);
- Operator actions that may need to be adjusted;
- Time since the plant was last shutdown;
- Whether the condition is during a forced outage or a planned outage; and
- If PWR and mid-loop operations are involved, the number of times the mid-loop state is entered.

- Download the latest SPAR model available for the plant in question. Examine the available ETs for at-power and/or SD modes in the model. If existing ET models that can be used with small modifications can be identified, copy and revise them. Also, examine the contents of the ET library for ET models that may be used with small revisions and import them if found. Make necessary changes to FTs and basic events, as needed. If the case requires major revisions, or totally new ETs, seek the assistance of the designated SD-cognizant person in your organization.

  Figure 7-2 shows a SD event tree template for a 4-loop Westinghouse PWR, taken from an existing SPAR-SD model, for the loss of RHR cooling event in plant Modes 4 or 5.

Almost all event tree top nodes contain “stub” fault trees, where a operator action defined specifically for this shutdown mode is “or-gated” with the system failure fault tree (to be transferred-in. Figures 7-3 and 7-4 illustrate two such “stub-FTs” for two of the top nodes of the event tree given in Figure 7-2.

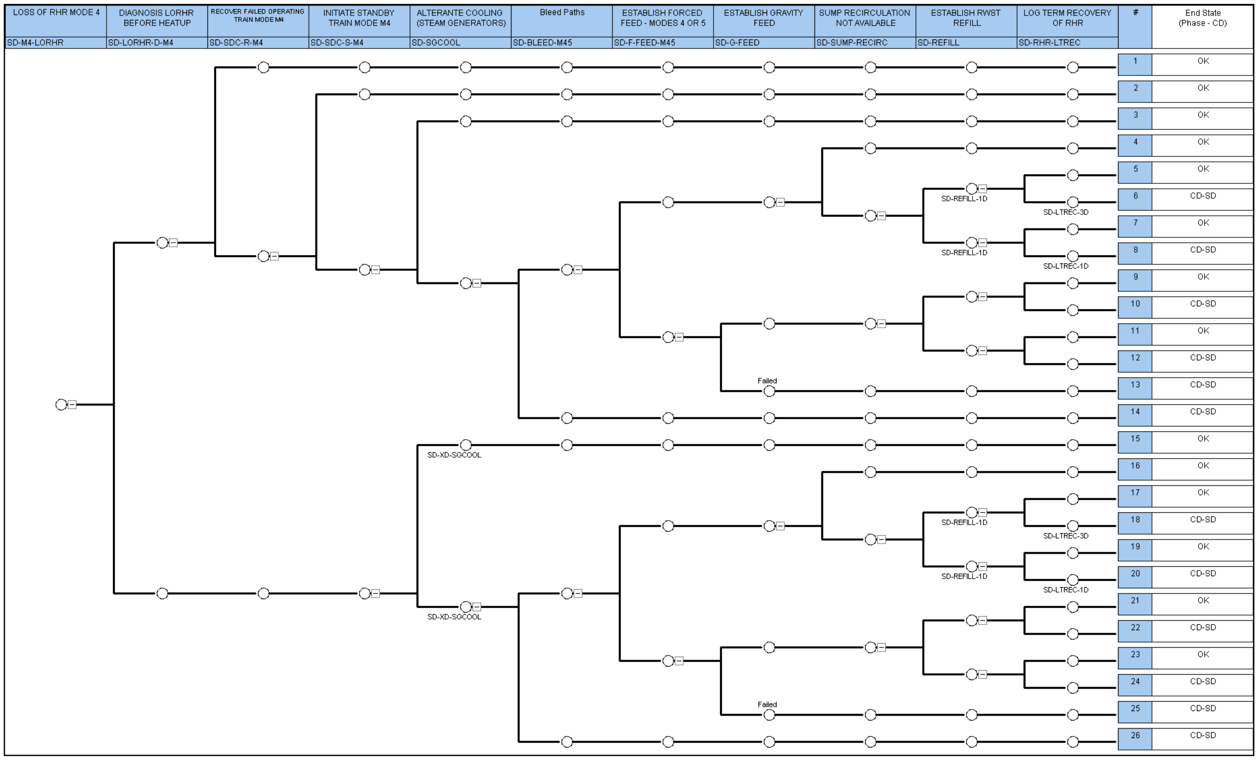


Figure 7-2. Example Event Tree for Loss of RHR Cooling Event

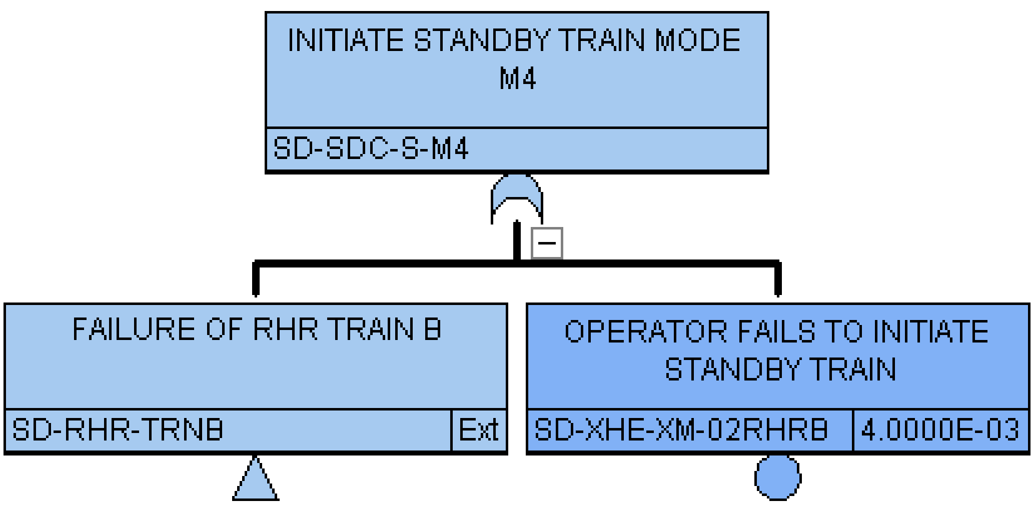


Figure 7-3. Stub-Fault-Tree for Event Tree Top “Initiate Standby RHR Train”[7,8]

[7] Basic event for a new (not present in the at-power model) SD operator action is defined. HEP calculated as 4E-03.

[8] New fault tree model made by copying a train of RHR from the at-power fault tree and setting T/M and other operator actions that do not apply to this SD state to zero (or removing them from the new fault tree).

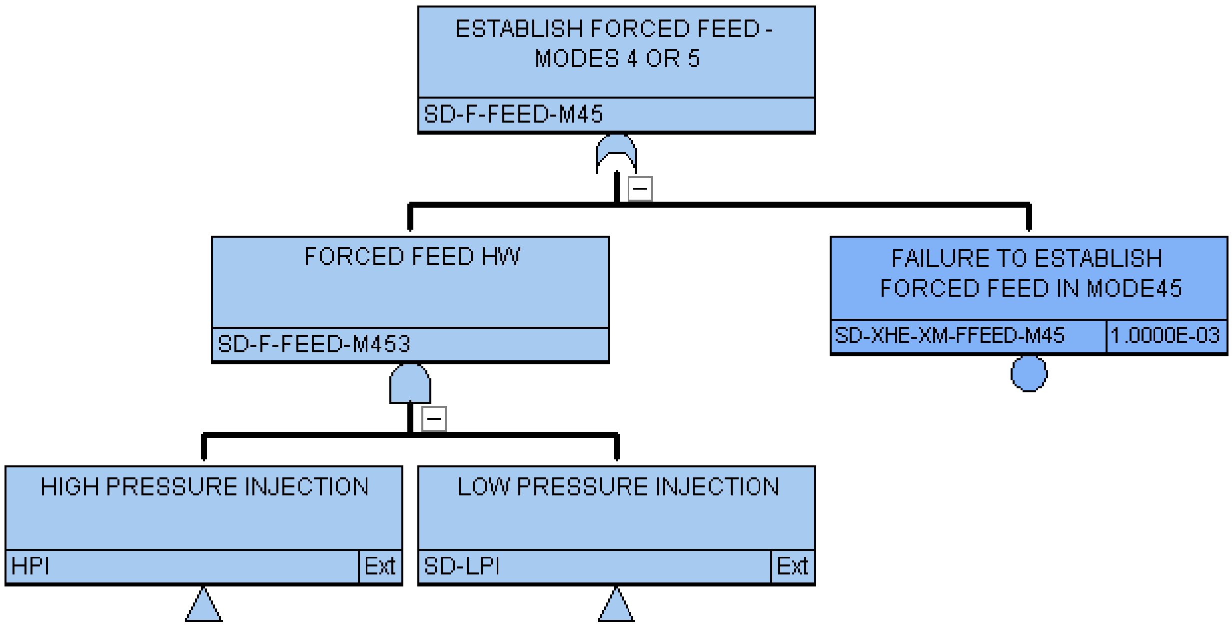


Figure 7-4. Stub-Fault-Tree for Event Tree Top "Establish Forced Feed"[9,10,11]

- Quantify the CCDP or CDP of the scenario by solving for the sequences of only those ETs that are involved in the scenario.

- Examine the cutsets to make sure that they reflect the intended scenario. Especially check operator action HEPs and validity of cutsets containing operator actions. Check for dependencies among operator actions. Modify as needed to obtain a proper estimate of risk for cutsets involving multiple operator actions. In the newer models built by MMG, dependencies are introduced by SAPHIRE basic event replacement rules; this is discussed in Appendix B.

[9] New fault tree SD-LPI is made by copying and modifying the low-pressure injection (LPI) fault tree from at-power model.

[10] Existing high-pressure injection (HPI) fault tree is used.

[11] Basic event for a new (not present in the at-power model) SD operator action is defined (HEP calculated as 1E-03).

8.0 Miscellaneous SD-Related Considerations

This section briefly discusses miscellaneous shutdown-related issues, and items that may be considered. Not all items are addressed yet in this version.

For each of these items, how they are addressed may be highly dependent on the individual plant and the specific event or condition being analyzed. If an existing SPAR-SD model is being used, then the analyst should review the model and model documentation to ensure that these issues are addressed in a way that is consistent with the details of the specific event or condition being analyzed.

8.1 Core Damage

It is assumed that the progression of a core damage (CD) sequence during shutdown operations will in most cases follow the steps such as:

- Boiling
- Core Uncovery
- Core Damage

In many cases, boiling or core uncovery times can be easily estimated, even by hand calculations, and are used as surrogates for core damage. The analyst must recognize that using these surrogates in SD models is deemed to be conservative. No attempt is made in this Handbook to define CD during shutdown operations; it can be taken as the same as core damage during at-power operations.

8.2 RHR Recovery in the Long Term

It is recommended that in a shutdown sequence, the sequence success criteria should always include long term recovery of RHR (or sustained operation of RHR). Temporary temperature control strategies (e.g., gravity injection) can be used as the means to gain time to repair/restore RHR, but not necessarily as a sufficient condition to declare sequence success (i.e., no core damage). A stable end state definition for a SD sequence should terminate with restoration of decay cooling (normally by RHR).

A simple long term RHR repair model is provided in the MMG.

8.3 Containment Integrity

In cold shutdown and refueling modes, the containment may be open and it may take time, at the order of hours, to close the containment hatches. This should be considered as a factor if fission product release is also analyzed. In refueling mode, if RCS boiling occurs, the effect of steam in operations in the containment and in securing the containment must be considered.

8.4 Sequence Mission Time

In some shutdown sequences, the time to core damage may be longer than 24 hours (for example in a loss of decay heat removal during refueling with reactor cavity filled and no loss of inventory event). The mission time for such sequences should be extended beyond the usual 24-hour period (see Volume 1, Section 4); until a sustainable safe state is reached. Such a longer time window may also allow crediting recovery/repair actions that may have not been feasible in a 24-hour period.

8.5 Shutdown Procedures

Availability of, or lack of, shutdown procedures specific to the event(s) being analyzed is crucial to the fidelity of the models. These procedures determine which operator actions and equipment are feasible to be credited. This point is also emphasized in the MMG and it is recommended that the first step in model construction should be to obtain the plant-specific procedures and make sure that the event trees reflect the realistic operator actions and hardware-human interactions.

8.6 Equipment Availability

In different shutdown operation modes, different trains of equipment may be taken out of service or aligned to other functions than normally expected. This type of equipment unavailability is not random, but is planned. Moreover, the list of unavailable equipment is likely to change from one shutdown mode or POS to the next. This equipment unavailability should be factored into the ET and FT models. MMG specifies identification of available equipment by the plant operational modes in question at an early stage of the modeling process.

8.7 Transition Risk and Low Power

Current version of this Handbook is limited to hot shutdown, cold shutdown, and refueling modes of the shutdown operations. It does not discuss low-power operation modes and transition risk.

8.8 Over-Drain Events during Mid-Loop Operation – PWR

The loss of inventory due to over-draining initiating event is defined as the operator error of over draining the reactor vessel when going to a mid loop condition in the RCS. This is not an actual RCS leak or LOCA that requires isolation; simply a case of when the operator is lowering level for mid loop operations, the RCS level was reduced to the point where RHR cooling was rendered inoperable (at least temporarily). The loss is assumed to terminate when the level drops below the bottom of the RCS loop hot leg). However, RCS makeup is required to re establish RHR cooling.

Since this initiating event is possible only during drain down to reduce inventory, it can only occur during the transition from POS M5 full inventory or POS-M6 to M5 reduced inventory. Also note that the loss of inventory at reduced inventory initiating event is a demand based initiating event. The demand (or opportunity for the failure event to occur) is the draining of the RCS to reach a mid-loop condition.

The initiating event demand-frequency for this event is initially set to two demands per outage, which is the expected number of times drain-down is expected in a refueling outage. This is followed by an even tree node that models the operator error of over-draining with a HEP of 1.8E 02 (taken from PWR models in Reference 1-3). The initiating event frequency may be zero if mid-loop is not entered in the shutdown of interest; it may be 2 if mid-loop is entered once to place the SG nozzle dams, and once to remove them. In one occasion, it was entered six times in a 30-hour period due to problems with leakage of the nozzle dams.

It should be noted that this event is caused by an operator error to terminate the drain-down. Ensuing operator actions postulated to deal with the event may need to be conditioned on the original operator error that caused the initiating event. Figure 8-1 illustrates the ET for over-drain events.

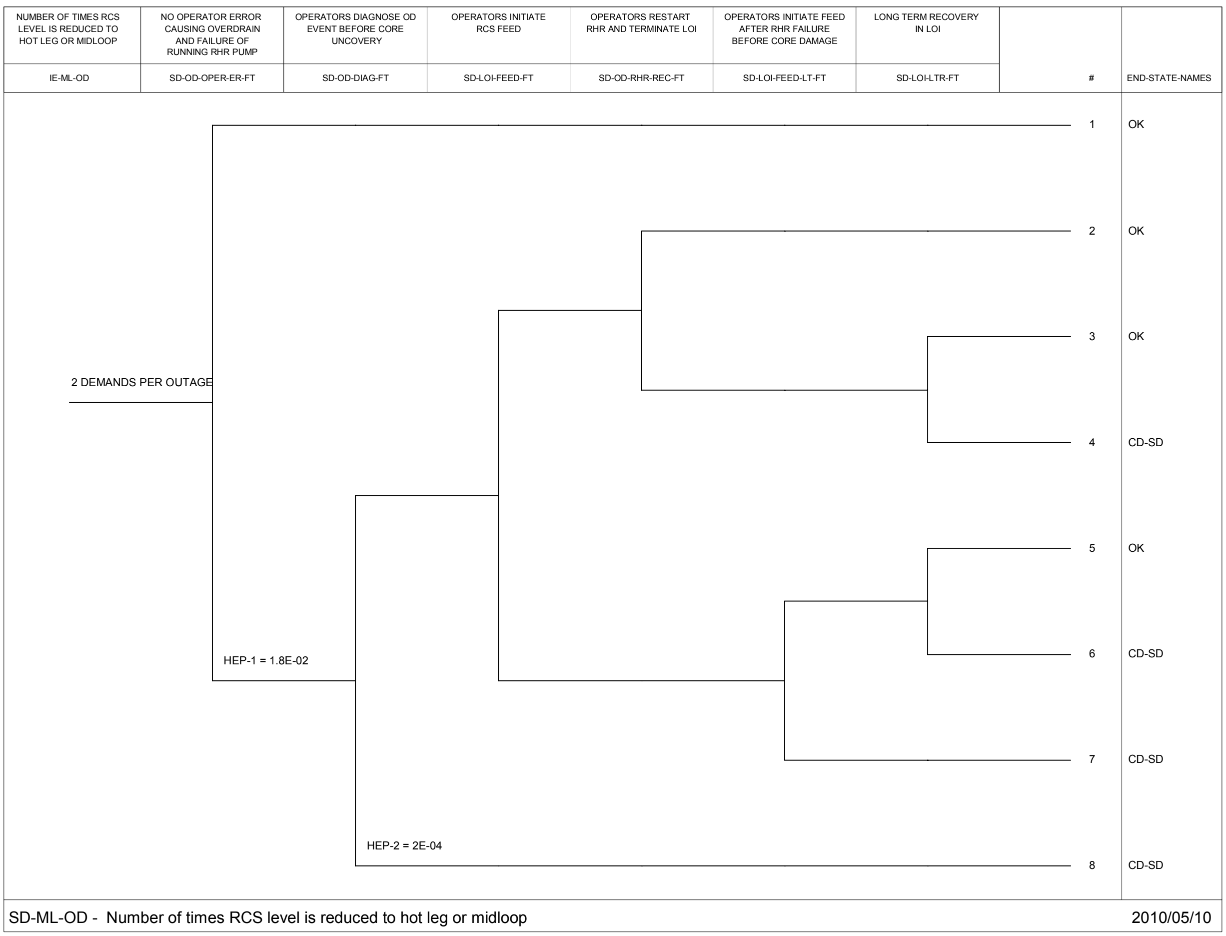


Figure 8-1. Template Event Tree for Over-Drain Event (ML-OD) for PWRs

Insights from past SD risk studies indicate that the CCDP of this event may be significantly higher than other initiating events. This is due to the fact that the event causes loss of RHR and also allows a short time window for recovery since the water level is very close to the top of the core and boiling will uncover the core in a relatively short time.

8.9 Decay Heat Time Windows

The amount of time that has passed since the reactor is tripped determines the decay heat level, thus the time to boiling if RCS is not cooled. The longer this time is the longer will be the time to boiling and the time to core damage, which allows more time for recovery and operator actions.

Four DH time windows are defined for the SPAR-SD models, as shown in Table 2-1. The concept of the plant being in a POS in an “early” DH time window, or a “late” DH time window is mentioned in the SPAR-SD models. DH time window should not be confused with the operator action time window, although the later DH time windows will allow longer operator action time windows.

8.10 System Success Criteria

The success criteria for the systems modeled may need to be adjusted for shutdown operations. For example, the number of pump trains required or dependence on pump room cooling are success criteria that may be different during shutdown than at-power.

The existing SPAR-SD models have already incorporated features in the system FTs to account for differences in shutdown success criteria. However, the success criteria can also depend on the details of the specific event or condition being analyzed. For example, if a LOI is being modeled, the size of the break flow will influence the number of pumps to be able to cope with the event and the operator action time windows. For smaller LOI events, less number of pumps may be sufficient and longer time windows for operator actions may be available.

8.11 Alarms, Interlocks, and Automatic Actions

During shutdown operations some of the alarms, interlocks, and automatic actions, which are normally active while at power, could be inactive or defeated. These issues can have considerable effects on the system response and operator response to an accident. An example may be an RHR automatic isolation signal on high pressure that is defeated during shutdown operations.

8.12 Electrical Power

Dependencies on electrical power sources can be different at shutdown conditions than at-power. This is especially true when electrical bus or diesel generator maintenance is being performed during an outage. The plant may use an alternate electrical line-up or add an additional diesel generator during shutdown. If these changes can be supported by plant shutdown procedures, then the shutdown model should credit them.

8.13 Valve Alignment

The alignment of certain key valves may be different during shutdown modes than at-power. Typically, basic events and fault trees are “borrowed” from the at-power model and used in the shutdown model. Due to the differences in valve alignment, some basic events may not be applicable in shutdown modes. Modifying the shutdown model to account for all valve line-up changes is likely not practical. Nevertheless, the shutdown model cutset results should be reviewed to see that any risk important basic events are actually valid for the shutdown POS.

An example of a valve alignment that can make an at-power basic event invalid is given here. An RHR heat exchanger service water supply valve may be normally closed during power operation, and a failure-to-open (FTO) The basic event is included in the at-power model. When the plant is shutdown, the same valve is normally open. For the purposes of a SD event analysis, the FTO basic event would not be valid.

Appendix A – Model and Data for Shutdown Events

A.1 Correspondence between Operating Modes and POSs

Table A-1 shows the correspondence between NUREG/CR-6144 POSs, technical specification operating modes, and SPAR POSs. This table is taken from SPAR-SD models, Table 1-4.

Table A-2 provides the POS naming convention.

A.2 Initiating Event Frequencies

Seven initiating event categories are defined for shutdown operations. The initiating event frequencies of these categories are given in Table A-3. Note that IESD OD “frequency” is actually a demand failure per entry to the applicable POSs (POS-M5ERVO, and POS-M5LRVO); it does not apply to the remaining ten POSs.

Table A-1. Comparison of POS Definitions

NUREG/CR-6144 POS	Description	Technical Specification Operating Mode (SPAR POS)
1	**Low Power Operation and Reactor Shutdown** • Turbine and Rx power levels are decreased to low power levels w/out causing Rx trip or loss of power conversion system (PCS) • Power at 10-15% • RCS temp (T_{ave}) is 547°F	Mode 1 - Power Operation
2	**Cooldown with SGs to 345°F** • Cooldown from 547°F and 2235 psig to RCS temp ~345°F and press ~345 psig	Mode 3 - Hot Standby
3	**Cooldown with RHR to 200°F** • Cooldown of Rx from 345°F to ≤ 200°F by controlled main turbine steam bypass (while maintaining SG pressure) • RHR is placed in service during hold • All engineered safeguard pumps (except one charging pump) is placed in pull-to-lock (PTL) • RCS pressure is maintained at 345 psig with a bubble in the pressurizer • Once RHR is in service SG steaming and RHR cooling is used to cooldown RC until SG pressure decreases to 5 to 15 psig (RCS temp 220 - 250°F)	Mode 4 (M4E) - Hot Shutdown Before Refueling (Early)
4	**Cooldown to Ambient Temperature (using RHR)** • RCS is cooled down from 195 to ~ 140°F by RHR heat exchangers flow control • RCS pressure is maintained at 345 psig with a bubble in Pressurizer	Mode 5 (M5EF) - Cold Shutdown Before Refueling (Early), Full RCS Inventory
5	**Draining the RCS to Mid-Loop** • Starting at 140°F with a bubble, the one operating RCP and pressurizer heaters are secured • The RCS is depressurized by spray down of the pressurizer and filling it	Mode 5 (M5EF) - Cold Shutdown Before Refueling (Early), Full RCS Inventory
6	**Mid-Loop Operations** • RCS at mid-loop, may be vented, the RC loops may be isolated	Mode 5 (M5ER) - Cold Shutdown Before Refueling (Early), Reduced RCS Inventory
7	**Fill for Refueling** • The Rx head is de-tensioned, unbolted, and removed • The water level is raised to flood the Rx • The upper internals are removed and stored underwater	Mode 5 (M5ER) - Cold Shutdown Before Refueling (Early), Reduced RCS Inventory
8	**Refueling** • With Rx head removed and refueling cavity flooded, the spent fuel assemblies are removed from the Rx core	Mode 6 (M6) Refueling
9	**Draining RCS to Mid-Loop after Refueling** • The Rx head bolts are tensioned	Mode 5 (M5LR) - Cold Shutdown After Refueling (Late), Reduced RCS Inventory

NUREG/CR-6144 POS	Description	Technical Specification Operating Mode (SPAR POS)
10	**Mid-Loop Operations after Refueling**	Mode 5 (M5LR) - Cold Shutdown After Refueling (Late), Reduced RCS Inventory
11	**Refill RCS Completely** • Water level is raised using CVCS • RCS is brought solid	Mode 5 (M5LF) - Cold Shutdown After Refueling (Late), Full RCS Inventory
12	**Heat-up Solid and Draw a Bubble** • The solid RCS is pressurized to ~345 psig	Mode 5 (M5LF) - Cold Shutdown After Refueling (Late), Full RCS Inventory
13	**Heat-up to 350°F** • Pressurizer ~345 psig, temperature controlled by RHR heat exchanger flow at 195°F	Mode 4 (M4L) - Hot Shutdown After Refueling (Late)
14	**Heat-up with SGs available** • The RCS and secondary systems continue the unit heat-up within heat-up rate limits	Mode 2 - Startup
15	**Rx Startup and Low Power Operation** • RCS pressure at 2235 psig, temperature at 547°F • Rx brought critical and power increased (<10%) to warm-up	Mode 1 - Power Operation

Table A-2. POS Naming Convention

POS naming convention is based on a six-character identifier that defines five different plant operating state characteristics:

Plant Mode
M4 Mode 4
M5 Mode 5
M6 Mode 6

Time Frame (in Relation to Refueling Mode)
E Early (before refueling)
L Late (after refueling)
X Not applicable (refueling mode)

RCS Inventory Status
R Reduced RCS inventory
F Full RCS inventory

RCS Pressure Boundary Status
V Vent open in the RCS pressure boundary
I Intact RCS pressure boundary

RCS Loop Status
B Blocked RCS loops (i.e., all steam generators are isolated from the rest of the RCS)
O Open RCS loops (i.e., RCS flow through the steam generators is possible)

For example POS-M6XFVB stands for plant is in mode 6; plant is in refueling mode; RCS is full; RCS is vented (open); RCS loops are blocked.

Table A-3. Davis-Besse LP/SD SPAR Model Initiating Events

Initiating Event Name	Description	Initiating Event Frequency (/yr)[12]
IESD-LORHR	Loss of decay heat removal capability (other than RHR loop isolation)	9.74E-03
IESD-ISOL	RHR loop isolation	4.87E-03
IESD-LOOP	Loss of offsite power	1.93E-01
IESD-LOAC	Loss of operating AC division	1.15E-01
IESD-LOI	Loss of inventory due to LOCA or recoverable diversion of RCS coolant	1.95E-02
IESD-LOLC	Loss of level control at reduced inventory	1.31E-01
IESD-OD	Loss of inventory at reduced inventory due to over-draining (demand-related rate)[13]	1.80E-02[b]

[12] Rates are given per shutdown year (except for IESD-OD).

[13] IESD-OD is the demand-related loss of inventory caused by the operator over-draining the RCS with the intent of reducing RCS level to mid-loop (or reduced inventory conditions). This SPAR value is per demand, and does not have time-based units.

Appendix B – Treatment of Operator Actions in Shutdown Scenarios

This subject is discussed in detail in Attachment A of the MMG. The contents of the attachment are repeated here for the convenience of the reader.

B.1 Process Steps

1. Obtain and refer to the plant-specific procedures.

2. Define operator action at the highest possible level – e.g. at the event tree node level, initially. Further breakdown can be done later on as needed. (See Figure B-1 for an example).

3. Fill out a task analysis form for each operator action defined, using the plant procedures for the shutdown conditions. (Table B-1-1)

4. Quantify HEP of each defined action without dependency considerations. Use SPAR-H plus the tables attached to the MMG.

5. Use the event tree picture to identify sequences with multiple operator actions and potential HEP dependencies. Mark these on the event tree picture (see example in Figure B-1-2). From these, define HEP dependency rules for multiple HEPs appearing in cutsets. Put these HEP dependency rules in SPAR-SD model recovery files (See example in Table B-1-2). Calculate HEPs for dependent actions. Refer to HEP dependency rules in Table B-1-3 for these calculations.

    5a. If an initiating event is caused by a human error, make sure that this is also considered for starting a chain of dependency rules.

6. Use Table B-1-4 to limit total HEP credit taken in a sequence based on sequence characteristics such as:

    6a. Sequence time window (STW) from the beginning of the first action to the no-return time for the last action to be credited.

    6b. Complexity of all the actions viewed together in the sequence.

    6c. Number of failed systems/trains/components; complexity of the failed equipment status.

    6d. Abundance or lack of multiple cues, team members, teams, checking and recovery opportunities in the sequence.

Key issues addressed:

- Keeping HEP basic event inflation from happening (e.g. number of basic events defined).

- Dependency modeling (including dependency on initiating event human errors).
- Sequence cutoff probability limit for HEPs.
- Systematic use and documentation of dependency rules and sequence cutoff credit given.

What is new?

- Weak dependence is introduced;
- Sequence cutoff probability is read off a table.

B.2 HEP Library

Previously calculated HEPs for SD events are assembled in a table of HEP library as a reference. Table B-2-1 illustrates the contents of this library.

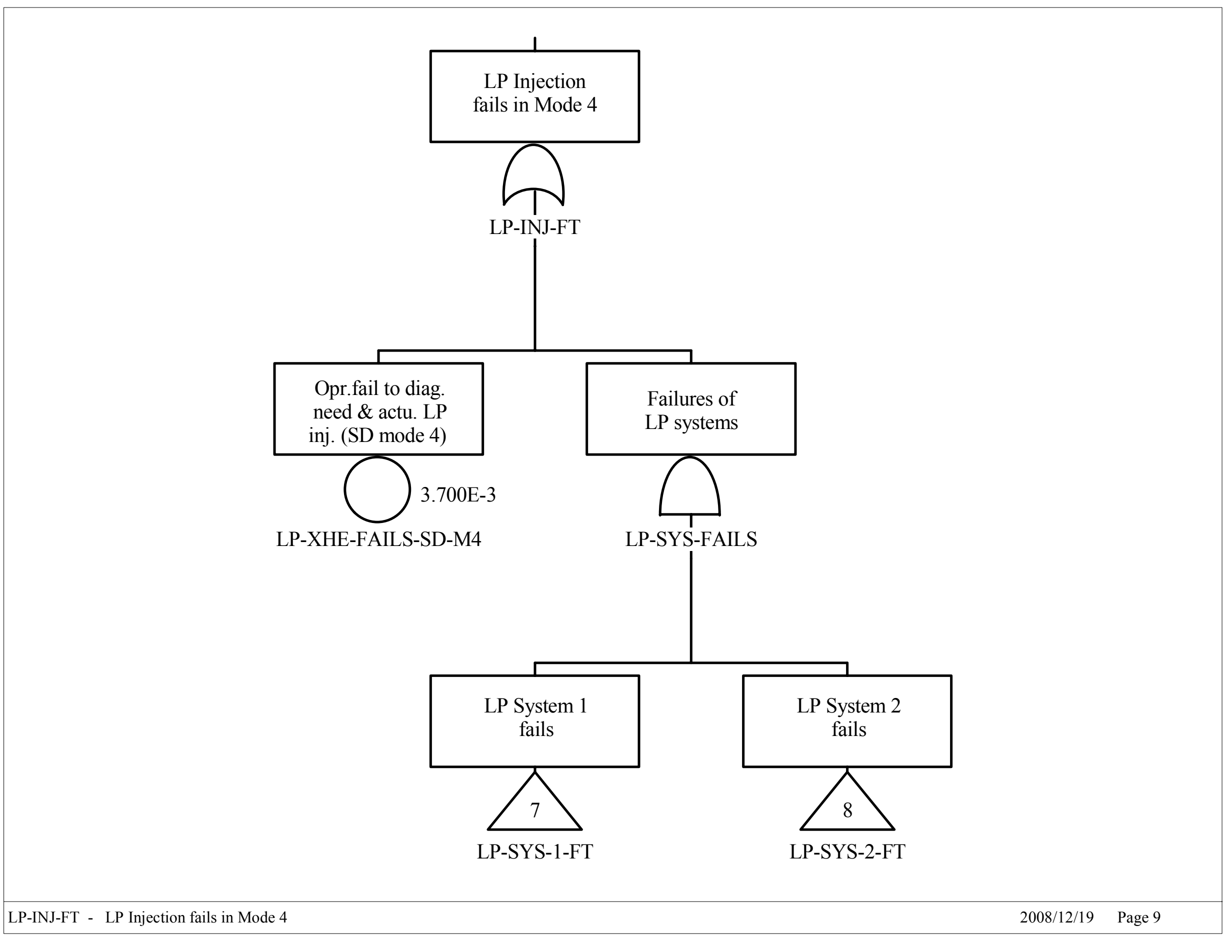


Figure B-1. Example Placement of HEP in Event Tree Node FT

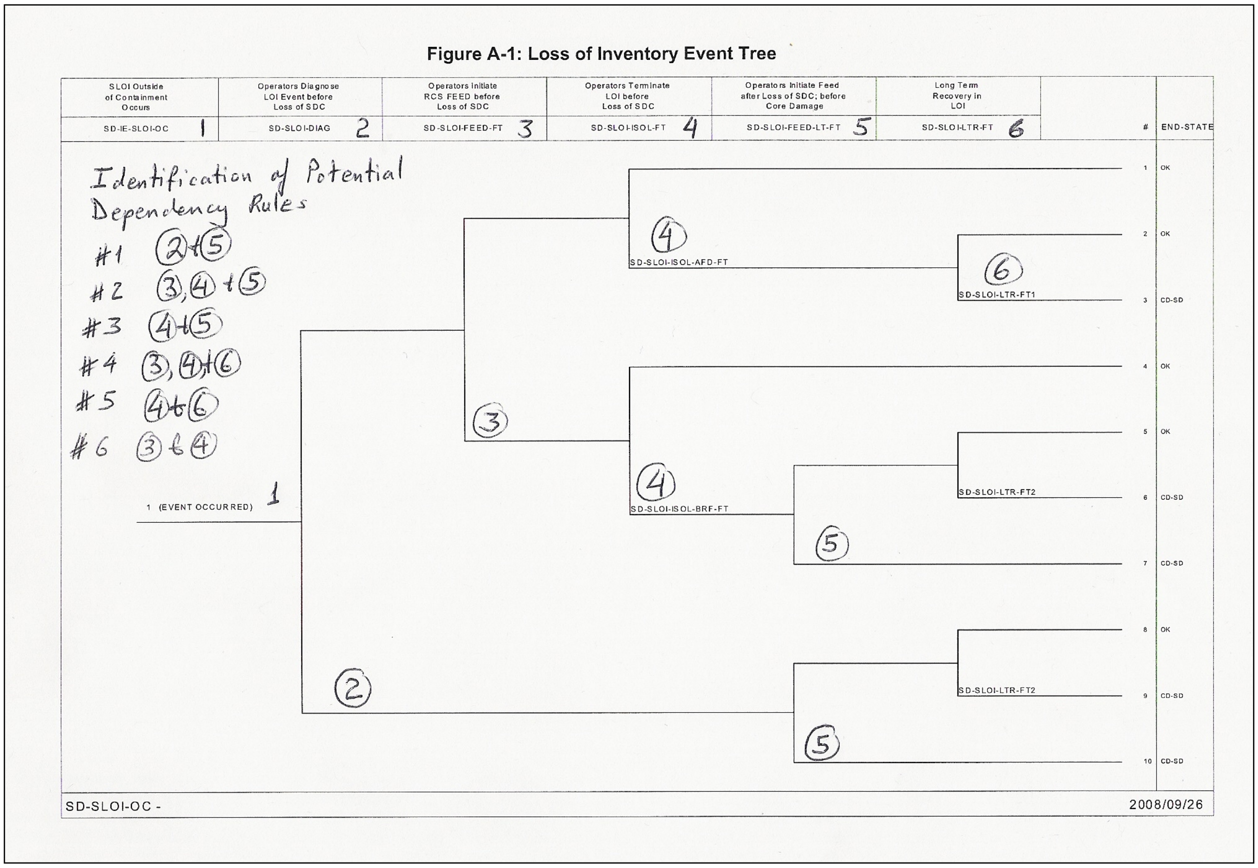


Figure B-1-2. Illustration of Marking Potential HEP Dependencies on an ET

Notes for Figure B-1-2:

The purpose is to identify rules for potential HEP dependencies in core damage sequences, including failure of an operator action that may have caused the initiating event.

- Label each ET node, including the initiating event by integers as shown. Assume each of the 6 nodes thus labeled may have an operator action as a single element cutset. If one node does not have such a HEP its integer is not used in the next steps.
- Examine sequences leading to core damage and containing consecutive failed operator actions. Label consecutive failed nodes with HEPs along a core damage sequence with the integer corresponding to the ET node (see Figure B-1-2 for illustration).

In this example, the initiating event does not have any operator failure. As an illustration, look at sequence 10 which has two consecutive operator actions, 2 and 5. This sets up rule #1 which will be placed in the SPAR-SD model recovery file as:

If HEP2 and HEP5 exist in the same cutset, replace HEP5 with HEP5D (dependent HEP5 is labeled as HEP5D in this case). In SAPHIRE recovery rules terminology, this rule will look like as follows:

```
if HEP2 * HEP5 then
    DeleteEvent = HEP5;
    AddEvent = HEP5D;
endif
```

- Note that if there is a successful ET node (containing a single-element cutset operator action) between two other failed event tree nodes with operator actions, it breaks the dependency. For example, in sequence 6, there is no potential dependency rule between HEP4 and HEP6, since success of node 5 with a successful HEP breaks a potential dependence.
- Note that sequence #7 provides 3 different potential dependency rules, one for HEPs 3, 4, and 5; a second one for HEPs 4 and 5; and a third one for HEPs 3 and 4.
- This example identifies and defines 6 potential dependency rules, which need to be analyzed to see if actual dependencies exist. If they do, then HEPs for each must be calculated and placed as additional basic events into the

SPAR-SD model. Then, the 6 recovery rules corresponding to these should be placed into the recovery rules file, in a separate paragraph at the end.

Table B-1-1. Example Task Analysis before HEP Calculation

HEP ID: SD-SLOI-DIAG-XHE

Task Analysis before HEP Calculation

1. Operator Action Description

This is diagnosis step that requires the operator to recognize the that an event has occurred, determine what type of event it is and determine which procedure(s) need to be used to address the event.

The control room received multiple annunciators when the electrical power slow transferred from the aux transformer to the backup transformer. The electrical transient also caused the running SDC pumps to stop momentarily while power swapped and both pumps restarted when power was returned.

The control room received no annunciators on the decreasing RCS level.

2. Other Failed Equipment / Events

Most of the electrical loads re-energized as the slow transfer progressed. However, the 1XP 600 volt AC attempted to re-energize but tripped on high in-rush current. It remained de-energized throughout the event and was not re-energized until several hours after the event. This complicated the event because it removed motive power from several front line systems that were required to mitigate the event. It did not impact any of the instrumentation that were required to diagnoses the event. However, it did distract the operators by adding to the cognitive work load.

3**. Operator Action Success Criteria**

The operator must recognize the abnormal event and start implementing the applicable procedure AP-26 “Loss of Decay Heat Removal”.

4. Cues

Decreasing level on control room indicators and associated computer displays feed from LT-5A and 5B. When level has decreased approximately 10 inches to a plus 60 inches a computer point alarm annunciated in the control room. However, the operators missed this annunciation as it was masked by many other computer points that were received due to the loss of power and subsequent re-energization.

A secondary cue was increasing level in the miscellaneous waste holdup tank (MWHUT). The combination of lowering RCS level and rising MWHUT level is indicative of a problem with the purification system.

5. Procedure + Relevant Steps

AP-26 “Loss of Decay Heat Removal” revision 20 was the controlling procedure for this event. It supplies the appropriate entry conditions in Step 1. The relevant entry conditions are:

- Loss of RCS inventory while on LPI DHR
- Loss of DHR capability as a result of loss of power

6. Main Control Room or Local Action

This is a main control room (MCR) cognitive event. The level indication is indicated in the control room. The reactor operator is responsible for monitoring the appropriate RCS parameters and the shift supervisor (SRO) is responsible for decision making.

7. Diagnosis (with or w/o recovery) / Execution (with or w/o recovery) / Diagnosis + Execution

This is a purely diagnostic event. If the operator fails to recognize that an event is occurring or fails to recognize that this is a loss of inventory event, there will be additional cues when the RCS level decreases sufficiently to perturb the SDC pumps. However, this second scenario will be evaluated with a second human failure event (HFE). Therefore, there is no recovery analyzed in this event.

8. Time Windows / Nominal / Mean / Median Actions Times

RCS level was decreasing at approximately one inch per minute. The indicated starting level was 70 inches; this is from a reference point of instrument zero at the center line of the hot leg. Shortly after reaching a level of 0, the running decay heat removal (DHR) pumps will need to be secured to prevent damage to them. This will be indicated to the operator by additional control room annunciators. Thus the time available for diagnosis and subsequent operator actions is approximately 70 minutes. The subsequent actions, however, will be handled by other HFEs.

As a point of reference, the operators recognized the event and entered the correct procedure in about two minutes.

9. Relevant Performance Shaping Factors

- *Time*: Additional time was available for this event.
- *Stress*: With a LOI event occurring stress was elevated. In addition to the LOI an additional stressor was the momentary loss of offsite power and a subsequent failure to re-energize the 1XP bus.
- *Complexity*: With the reactor in cold shutdown, the operators' primary focus is on reactor level and temperature. The RCS level was being displayed on multiple monitors in the MCR. The operators monitored this parameter by looking for a flat line response on the displays. A flat line indicated that level was being maintained as desired. A decreasing level indicated a problem. However, there were no direct annunciators on this parameter. The first MCR annunciator would not be received on this parameter until 70 minutes after the event initiation. There was a computer point alarm that was received about 10 minutes after the event initiation, however, the operators missed this cue. Finally, the entry conditions for this procedure were straightforward and simple and the operators were well trained on them.

10. Define Subtasks / Failure Modes / Assign BE ID(s)

- Subtasks: There are none.
- Failure modes:
  Operator fails to recognize RCS level is decreasing.
  Operators recognize that level is decreasing but fail to enter the correct procedure.
- BE ID: SD-SLOI-DIAG-XHE

Table B-1-2. Example HEP Dependency Rules in the SAPHIRE Project Recovery File

```
|SD – SAPHIRE Recovery Rules for Conditional HEP Substitutions in SD CDF Cutsets
|Rule 1: 2,6

if SD-SLOI-DIAG-XHE * SD-SLOI-ISOL-BCD-XHE then
     DeleteEvent = SD-SLOI-ISOL-BCD-XHE;
     AddEvent = SD-SLOI-ISOL-BCD-XHE-D1;

|Rule 2: 3,5,6

elsif SD-SLOI-FEED-XHE * SD-SLOI-ISOL-BRF-XHE * SD-SLOI-ISOL-BCD-XHE then
     DeleteEvent = SD-SLOI-ISOL-BRF-XHE;
     DeleteEvent = SD-SLOI-ISOL-BCD-XHE;
     AddEvent = SD-SLOI-ISOL-BRF-XHE-D2;
     AddEvent = SD-SLOI-ISOL-BCD-XHE-D2;
endif
```

Table B-1-3. HEP Dependency Rules

q2 is potentially dependent on q1

Dependency Level	Calculation of q1	Example with q2= 0.01	Small q2 Approximation
No Dependency	q2	0.01	q2
Weak dependency	(1+99*q2) / 100	0.02	0.01
Low dependency	(1+19*q2) / 20	0.06	0.05
Medium dependency	(1+6*q2) / 7	0.15	0.15
High Dependency	(1+q2) / 2	0.51	0.5
Complete dependency	1	1	1

Notes:

1. All dependency levels except for “weak dependency” are defined in SPAR-H.

2. Weak dependency level is introduced to give analysts more modeling options, especially with longer time windows that may be available in shutdown operations: use weak dependency when two HEPs are in a sequence with a large time window; actions are simple; abundant or clear cues exist, yet no dependence cannot be postulated.

Table B-1-4. Sequence Cutoff Probabilities

Hour	Case-1 Complicated	Case-2 Nominal Case	Case-3 Simple
1	1.0E-03	1.0E-04	1.0E-05
8	1.0E-04	3.0E-05	1.0E-06
12	3.0E-05	1.0E-05	3.0E-07
16	1.0E-05	1.0E-06	1.0E-07
24	1.0E-06	1.0E-07	1.0E-08
48	1.0E-07	1.0E-08	< 1E-08

- Do not use if the total time window is less than 1 hour.
- Measure sequence time window (STW) from the beginning of first action to point of no return time of last action.
- This time window may be less than the total time to core damage.
- Use geometric interpolation for other hours not shown in the tables.

Use the following three criteria to select a case; if the sum is 2 or 3, assign a case; otherwise keep going with the tie-breaker criteria 4, 5, 6 to assign a case. (The numbers are placed for illustration; ignore them when using this process.)

		No	Maybe	Yes
1. Abundant and Clear Cues; New Ones in Time		1		
2. Simple Event			1	
3. Few Equipment Failures		1		
	Sum =	**2**	**1**	**0**
	Assign to case	**Case 1**	Case 2	Case 3

<u>Tie Breaker</u>

4. All actions Proceduralized
5. All actions in MCR
6. All actions in Simulator Training
7. Change from Emergency Operating Procedures/Emergency Response Guidelines to FRGs (Change of Procedure)

Tie Breaker Sum =

Table B-2-1. HEP Library (partial list for illustration)

Plant	Oconee
Initiating Event	Small Loss of Inventory during Cold Shutdown

Human Error Event	Description	Controlled by OPs Crew	Time Available	Mean Diagnosis HEP	Mean Action HEP	Total Mean HEP	Comments
SD-SLOI-DIAG-XHE	Operator fails to diagnose small LOI outside of containment before loss of SDC	One	30 min	1.0E-03	N/A	1.0E-03	Extra time, simple
SD-SLOI-FEED-XHE	Operator fails to initiate feed before loss of SDC	One	40 min	2.0E-03	4.0E-03	6.0E-03	High stress, obvious diagnosis, procedures less than desirable
SD-SLOI-FEED-LT-XHE	Operator fails to initiate feed after loss of SDC, before core damage	One	90 min	2.0E-04	1.0E-03	1.2E-03	Extra time, obvious diagnosis, high stress, poor procedures
SD-SLOI-ISOL-AFD-XHE	Operator fail to terminate SLOI leak before RWST is depleted	Two	~30 hrs	N/A	1.0E-05	1.0E-05	Extra time,
SD-SLOI-ISOL-BRF-XHE	Operator fails to terminate SLOI leak before SDC fails	One	40 min	N/A	2.0E-03	2.0E-03	High stress
SD-SLOI-LTR1-XHE	Operators fail to refill BWST as part of long-term recovery	Two	~30 hrs	1.0E-05	4.0E-04	4.1E-04	Extra time, obvious diagnosis, moderate complexity, incomplete procedures
SD-SLOI-LTR2-XHE	Operators fail to restart LPI in SDC mode as part of long-term recovery	Two	~30 hrs	N/A	2.0E-04	2.0E-04	Extra time, moderate complexity

Notes:
1. An HEP below this value will push into reliability range of automatic actuation logic
2. Estimated TTB = 20 minutes
3. Estimated TTCD is 90 minutes if drain down continues to mid-loop
4. Success criteria > 100 gpm
5. Source: ML0832604041
6. N/A = Not Applicable