A methodology for Level 2 PSA evaluation with consideration of specific features for Low Power Shutdown Probabilistic Safety Assessment

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1. Introduction

The primary objective of the Level 2 PSA during Lower Power/Shutdown (LPSD) operation is to provide insights into potential plant vulnerabilities with regard to accident progression. The shutdown risk information can be used to provide the information to develop outage risk management guidelines. This includes Plant Damage State (PDS), Containment Event Tree (CET), Source Term Category (STC), and Containment Ultimate Pressure Capacity (UPC) analyses. The LPSD Level 2 analysis utilizes much of the at-power Level 2 analysis for bounding, conservative treatment of severe accident phenomena. But, for some portions of the analysis including Plant Operational States (POSs), LPSD-specific evaluations such as UPC related to the containment Equipment Hatch (E/H) with 4 bolts, Reactor Coolant System (RCS) Not Intact for severe accident phenomena are desired for realistic evaluation.

2. Methods and Results

In this section some of the techniques used to model the LPSD Level 2 are described. The LPSD Level 2 model includes PDS, CET, STC, UPC, and Thermal Hydraulic Analysis for CET models.

2.1 LPSD Level 2 Methodology Overview

This analysis included quantitative evaluation of the large release frequency (LRF) for internal events during LPSD operation modes. Some lower CDF POSs are evaluated conservatively, with a more detailed evaluation being performed for POSs with the more significant contributors to the LPSD CDF.

Many of the LPSD Level 2 phenomenological considerations such as containment isolation except for E/H with 4 bolts and containment over-pressurization are the same as in the at-power analysis. But some require specific analysis in LPSD Level 2. For example, in some POSs, the containment equipment hatch can be open, which must be considered as a potential release path. The most significant differences between the at-power and LPSD Level 2 analyses occur in those POSs with RCS open, so the LPSD Level 2 performs specific analyses in those POSs, with additional consideration given to the POSs in which the containment E/H can be open.

2.2 POS Classification

The followings are identified to classify POSs and POS classification is summarized in Table 1.

- Technical Specifications (TS)
- The Level of Core Decay Power
- The Level of RCS water and pressure
- The Primary temperature
- The States of RCS such as the RCS open parts (i.e., pressurizer manway, SG manway, pressurizer vent valves, the head of reactor vessel, and ICI tube)
- Plant Equipment Arrangements
- Success Criteria of Mitigating Systems for Abnormal Accident
- The Availability of Mitigating System
- The maintenance of front and auxiliary system
- System Design Feature
- The decay heat removal mechanisms
- Containment Status
- Before or after the Refueling
- The Outage Experience of Reference Plants.

Table 1. POS Classification

POS	Description	Factors for POS Classification	
1	Reactor trip and Subcritical operation	The Level of Core Decay Power Mode 3 (Hot Standby)	
2	Cooldown with Steam Generators to 350°F		Residual Heat Removal System Mode 4 (Hot Shutdown, SCS operation)
3A	Cooldown with Shutdown Cooling System to 212°F	Mode 5 (Cold Shutdown, The Primary temperature of < 212°F(100°C) Containment Isolation Status	
3B	Cooldown with Shutdown Cooling System to 140°F		The level of RCS pressure down to the Atmosphere
4A	Reactor Coolant System drain-down (pressurizer manway closed)	Pressurizer Manway Open	
4B	Reactor Coolant System drain-down (manway open)		The level of RCS water at reduced inventory operation Nozzle dam installation
5	Reduced Inventory operation and nozzle dam installation	Mode 6 (Refueling)	
6	Fill for refueling		
7	Offload	Core Location Change	Core Alterations
8	Defueled		
9	Onload		
10	Reactor Coolant System drain-down to Reduced Inventory after refueling	Mode 6 (Refueling)	The level of RCS water at reduced inventory operation Nozzle dam removal
11	Reduced Inventory operation with steam generator manway closure		
12A	Refill Reactor Coolant System (pressurizer manway open)	Pressurizer Manway Close	
12B	Refill Reactor Coolant System (manway closed)		The level of RCS pressure up from the Atmosphere
13	Reactor Coolant System heat-up with Shutdown Cooling System to 212°F	Mode 4 (Hot Shutdown, The Primary temperature of > 212°F(100°C) Containment Isolation Status	
	Reactor Coolant System heat-up with Shutdown Cooling System to 350°F		Residual Heat Removal System Mode 3 (Hot Standby, SG operation)
14	Reactor Coolant System heat-up with steam generators	The Level of Core Decay Power Mode 2 (Startup)	
15	Reactor startup		

2.3 Plant Damage States (PDSs) analyses

The PDS characteristics are defined by selecting system operations considered to be important to the parameters such as accident progression in the containment, time, mode, and location of containment failure, and the radionuclide source term. The

parameters used to define the PDSs include the functional status of important systems, variables determined by systems operation (e.g., RCS pressure, RCS Intact/Not Intact), accident initiator type, and the timing of events. The POSs and initiating events applicability are summarized in Table 2.

Table 2. POS and Initiating Events Applicability

No	Acronym	Parameter Description	Parameter value	POS Applicability	I.E. of LPSD	I.E. of Full Power
1	CONBYP	Containment Bypass	ISLOCA	1,2,14,15	N/A	ISLOCA
			SGTR	1,2,14,15	N/A	SGTR
			BYPASS	3A~6,10~13	JL w/o CHR	-
			NO BYPASS	3A~6,10~13	ALL	-
2	CONISO	Containment Isolation	ISO	3A~6,10~13	ALL	-
			NOTISO	3A~6,10~13	ALL	-
			RBCM	3A~6,10~13	ALL	-
3	RCSINT	RCS Intact or Not Intact	INTACT	3A~4A,12B~13	S1,S2,JL,LP,LX,CC,TC,KV	-
			NOTINTACT	4B~6,10~12A or LTOP StuckOpen at 3A~4A,12B~13	ALL	-
4	RCSINV	RCS Inventory Level	NORMAL	3A~4B,6,10,12~13	S1,S2,JL,LP,LX,CC,TC,KV	-
			REDUCED	5,11	ALL	-
5	RCSPRE	RCS Pressure	High	1,2,14,15	N/A	-
			Medium	3A~4A,12B~13	S1,S2,JL,LP,LX,CC,TC,KV	-
			Low	4B~6,10~12A or LTOP StuckOpen at 3A~4A,12B~13	ALL	-
6	INVINJ	Status of Invessel Injectio n	ON	3A~4A,12B~13	ALL	-
			FAILED	3A~4A,12B~13	ALL	-
			RECOVERED	3A~4A,12B~13	LX(SBO)	-
7	RELPOT	Release Point Change by 3 Way Valve	INC	4B~6,10~12A or RELPOT-SUCCESS	ALL	-
			IRWST	RELPOT-FAILED at 3A~4A,12B~13	S1,S2,JL,LP,LX,CC,TC,KV	-
8	CHRSTA	Containment Heat Remo val Availability	CHR-NOT	3A~4A,12B~13	ALL	-
			NOCHR	3A~4A,12B~13	ALL	-
			RECOVERED	3A~4A,12B~13	LX(SBO)	-
9	CAVCON	Containment Cavity Con dition	WET	3A~4A,12B~13	ALL	-
			DRY	3A~4A,12B~13	ALL	-

2.4 Containment Event Tree (CET) analyses

The purpose of the CET quantification is to assess the relative likelihood or probability of each distinct containment end state on the PDS associated with the CET. This is accomplished by assigning a probability to each branch in the CET and propagating (or combining) the probabilities for each pathway leading to a distinct containment end state.

The approach to the LPSD Level 2 CET is similar to the at-power Level 2 analysis. For POSs 1, 2, 3A, 13, 14 and 15, the containment integrity is required by Technical Specifications (TS) when operating Modes are 2, 3, 4. The accident progression of these POSs can conservatively be estimated using the at-power conditional probability of a large release.

For POSs 3B and 4A, the RCS is closed, but for portions of each POS, the containment E/H may be open. The mitigation for closing containment must be considered. Failure to close containment is assumed to result in a large release while successful closure is addressed in the same manner as POSs 1 ~ 3A and 13 ~ 15.

For POSs 4B ~ 12A, the RCS with large open parts is not Intact, there is the potential for an accident progression that is substantially different compared to the at-power Level 2 analysis. For example, POSs in which the pressurizer manway or Steam generator Inlet Plenum is open will always be at Low pressure, so containment failure due to High Pressure Melt Ejection (HPME), Direct Containment Heating (DCH), etc. is not credible. The containment failure modes at POSs are summarized in Table 3. For POSs 10 ~ 13 after refueling, Containment Failure Modes are the same with POSs 3 ~ 6. POSs 7 ~ 9 are not evaluated in this evaluation.

Table 3. Containment Failure Modes at POSs

POS No	Contents	Mode	Containment Failure Mode
POS 1 Intact	Reactor trip and Subcritical operation	1, 2	ECF - Alpha, HPME/DCH, H2 Burn & DDT LCF - Overpressure Induced LCF, H2 Burn & DDT, BMT Others - Iso.-Fail, Bypass
POS 2 Intact	Cooldown with Steam Generators to 350 °F	3	ECF - Alpha, HPME/DCH, H2 Burn & DDT LCF - Overpressure Induced LCF, H2 Burn & DDT, BMT Others - Iso.-Fail, Bypass
POS 3A Intact	Cooldown with Shutdown Cooling System to 212 °F	4	ECF - Alpha, HPME/DCH, H2 Burn & DDT LCF - Overpressure Induced LCF, H2 Burn & DDT, BMT Others - Iso.-Fail
POS 3B Intact	Cooldown with Shutdown Cooling System to 140 °F	5	ECF - Alpha, HPME/DCH, H2 Burn & DDT LCF - Overpressure Induced LCF, H2 Burn & DDT, BMT Others - Iso.-Fail
POS 4A Intact	Reactor Coolant System drain-down (pressurizer manway closed)	5	ECF - Alpha, HPME/DCH, H2 Burn & DDT LCF - Overpressure Induced LCF, H2 Burn & DDT, BMT Others - Iso.-Fail
POS 4B Not Intact	Reactor Coolant System drain-down (manway open)	5	ECF - H2 Burn & DDT LCF - Overpressure Induced LCF, H2 Burn & DDT, BMT Others - Iso.-Fail
POS 5 Not Intact	Reduced Inventory operation and nozzle dam installation	5	ECF - H2 Burn & DDT LCF - Overpressure Induced LCF, H2 Burn & DDT, BMT Others - Iso.-Fail
POS 6 Not Intact	Fill for refueling	5, 6	ECF - H2 Burn & DDT LCF - Overpressure Induced LCF, H2 Burn & DDT, BMT Others - Iso.-Fail

2.5 Source Term category (STC) analyses

The end points of the containment event tree represent the outcomes of possible accident progression sequences. These end points describe complete severe accident sequences from initiating event to release of radionuclides to the environment. The LPSD Level 2 evaluation utilizes the same definitions of at-power Level 2. The LPSD release category evaluation is less detailed, as a detailed evaluation in each of the POSs would yield hundreds of release categories.

2.6 Containment Ultimate Pressure capacity (UPC) analyses

The containment E/H can be secured in LPSD POSs with 4 bolts, but this provides a lower containment ultimate pressure capacity than credited in the at-power Level 2. The LPSD analysis performed specific Finite Element Method (FEM) analyses.

It was found that equipment hatch failure limits the containment pressure capacity and governs the UPC as a containment pressure. The analysis Result of E/H with 4 bolts is showed in Fig. 1.

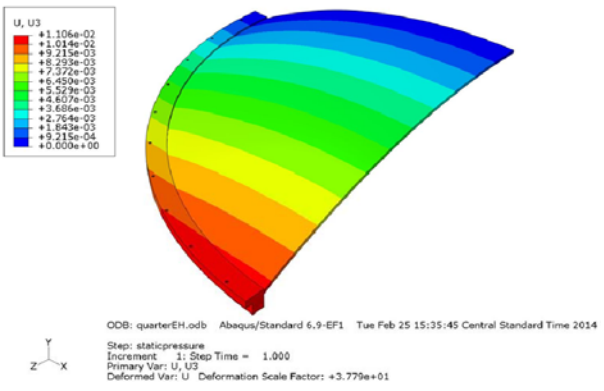

Fig. 1. The analysis Result of E/H with 4 bolts

3. Conclusions

All POSs are evaluated for their Large Release Frequency (LRF). Some POSs are evaluated conservatively utilizing the at-power models, and other POSs are evaluated in specific analysis. The overall LPSD Level 2 model is evaluated. If the containment E/H and one of the two doors on each of the personal air locks are closed as containment is operable at reduced RCS inventory operation, LRF is expected to be less than 10% of LPSD CDF.

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