A methodology for determining of Plant Operating States of Low Power Shutdown Probabilistic Safety Assessment for the next-generation Nuclear Power Plants

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Abstract: This paper outlines the Low Power Shutdown (LPSD) Probabilistic Safety Assessment (PSA) portion of a methodology for the determination of the Plant Operating States (POSs). This is to determine how best to characterize them for inclusion into the LPSD PSA. The characterization of POS will begin a review of available shutdown PSA studies for current generation plants. The next-generation Nuclear Power Plants (NPPs) provide useful references for POS development. Several sets of current and next-generation NPPs including NUREG/CR-6144 of Surry Unit 1 shutdown PSAs have been reviewed to identify potential POS. The POS defined for the next-generation NPP PSA must represent all conditions that can occur over the course of a fuel cycle. This paper considers all plant conditions except full power operation which is addressed with the internal events PSA. The development of POSs can lead to group plant states that require similar equipment, timing, and operator action to respond to an upset condition. POS Grouping is based on Technical Specifications (TS) requirement as well as key factors associated with the main shutdown risk contributors like RCS temperature, RCS pressure, RCS inventory, State of RCS pressure boundary, and Decay heat levels.

Keywords: PSA, LPSD Level 1, POSs

1. INTRODUCTION

The purpose of this paper is to identify unique plant operating states (POSs) during Low Power Shutdown (LPSD) operation. POSs will cover the LPSD evolution from full power operation to refueling conditions. During shutdown states, initial conditions, such as decay power and primary pressure, differ significantly from conditions during power operation.

The first step in evaluating each core damage sequence is the determination of POS. In the POS analysis, a thorough and systematic search was performed to define the spectrum of potential POS for the next-generation NPP. The available studies were reviewed to identify potential NPP shutdown states. In addition, the design control documents for the next-generation NPP were also reviewed to determine whether the current generation POS list was expected to remain applicable or not.

The POSs are expected operating conditions. These states are based on the existing outage practices common to all PWRs. It is expected that outage practices for the next-generation NPP will be similar to existing outage practices but POS for the next-generation NPP reflecting plant specific design feature can be developed. The developed POS can be used for the next-generation NPP PSA. The development includes planned shutdown refueling as well as unexpected shutdowns for unplanned maintenance and other events. As a result, the scope of potential states has been established. The task is to determine how to best characterize them for inclusion into the LPSD PSA.

The full power PSA is based on assumption that the plant power is 100%. But the POSs are various because the operational mode is changed as the process of planned outage. The LPSD operation encompasses low power operation, hot & cold shutdown process to cool RCS after reactor trip, disassembly work of reactor internals for refueling preparation, refueling, maintenance and test for equipment and components, assembly work of reactor internals. Plant equipment arrangements should be changed in order to do each process during LPSD. The success criteria of mitigating systems for

abnormal accident like loss of Shutdown Cooling System (SCS) are dependent on the changing of plant arrangement. For example, for loss of SCS during LPSD operation, time to boiling and core damage is dependent on the level of decay heat and the area of RCS open part. Thus, in order to evaluate LPSD PSA, it needs to classify various plant configuration and operational conditions into several POSs and each POS should be applied by the same success criteria conservatively.

The next-generation technical specification (TS) can lead to group operational states into six operational modes based on reactor criticality, the temperature and pressure of RCS. But operational modes of TS are limited to reflect various and complicate plant operational states such as level changing of RCS water and refueling during LPSD. POSs are detailed plant arrangements based on six operational modes of TS and delivers basic information for LPSD PSA.

The POSs of the next-generation NPP are based on operational procedures and the POS classification of reference plants.

2. POS Characterizations for LPSD Level 1

The first step in LPSD PSA analysis is to identify POSs. Due to the continuously changing plant configuration in any outage, POSs are defined and characterized within each outage type. Each POS represents a unique set of operating conditions (e.g., temperature, pressure, and configuration).
In general, a POS is characterized in terms of TS mode(s), RCS conditions (RCS liquid inventory and SG availability), and RCS vent status. The TS mode determines the bounding RCS temperatures and pressures of the reactor core. The key safety functions during LPSD are considered to define and characterize each POS.

The POSs can be defined for the various purposes. For the evaluation of core damage frequency during the LPSD states, the parameters related to the RCS and core are focused on items as the POS classification factors.

2.1 Review of Potential Plant Operating States

The characterization of POS will begin with a review of available shutdown PSA studies for current generation plants. Several sets of current and next-generation NPPs shutdown PSAs have been reviewed to identify potential POS. These are summarized below.

○ Current-Generation Reactor Analyses

NUREG/CR-6144 (Reference 1) documented a shutdown PSA for Surry Unit 1 in 1994. It included a comprehensive set of POS that correlate well with those selected for the next-generation NPPs.

○ Certified Designs for Next-generation NPPs

The NRC has certified the Westinghouse System 80+, AP600 and AP1000 designs (Reference 2). The AP1000 report includes a shutdown PSA.

○ Next-generation NPPs Designs under Review

The NRC is reviewing Mitsubishi's US-APWR (Reference 3) and AREVA's EPR (Reference 4) for design certification. Both designs include LPSD PSA analyses. An AP1000 amendment is under review. These sources have the advantage of all being relatively recent (2011) documents.

Both the US-APWR and EPR analyses include a set of POSs that are very similar to those in NUREG/CR-6144. The published AP1000 discussion omits many details of the shutdown PSA, such that the POSs are not listed. The AP1000 discussion does note that drain-down evolutions and reduced inventory conditions are the dominant shutdown states. The AP1000 amendment does not

propose any changes to the shutdown analysis as documented in the original, approved design control document.

○ Summary of POS Survey

The POS listed in the documents discussed above are summarized in Table 1. Comparing the POS horizontally across the rows, it is clear that the POS for each of the studies is similar, but POS reflecting plant specific design feature is developed.

○ Plant-Specific Experience

The plant-specific experience requires the consideration of plant-specific operating information, based on review and incorporation of plant-specific operating experience into the PSA, interviews with plant operators and other personnel, plant walkdowns, etc. Substantial industry experience with similar pressurized water reactors is available to confirm that the selected set of POSs is appropriate for next-generation NPP. However, as these reactors are currently in the design stage, no plant-specific experience has been acquired to date.

○ General Assumptions and Notes

The following are general assumptions and notes applicable to the POS development:

- Plant conditions that exist in forced outages result in no unique plant conditions not seen in refueling outages.
- The conduct of next-generation NPP outages will be similar to those performed for operating NPPs.

Table 1. POS Definitions from Various Sources

NUREG/CR-6144 Section 3.5 (June 1994) (Reference 1)	**US-APWR Table 19.1-81 (Mar. 2011) (Reference 3)**	**EPR Table 19.1-87 (Aug. 2011) (Reference 4)**
(1) Low Power Operation & Reactor Shutdown	(1) Low power operation (*)	(A) Power Operation (**)
(2) Cooldown with Steam Generators to 345°F	(2) Hot standby condition (*)	(B) Hot Standby to T > 248°F; (**)
(3) Cooldown with Residual Heat Removal to 200°F	(3) RHR cooling (RCS full)	(CAd1) RHR: RCS Normal Level with 2 RHR and SG (shutting down) (CAd2) RHR: RCS Solid with 4 RHR and SG (shutting down) (CAd3) RHR: RCS Solid 4 RHR (shutting down)
(4) Cooldown to Ambient Temperatures (using RHR)		
(5) Draining the RCS to Mid-loop	(4) RHR cooling (mid-loop operation)	(CBd) Mid-loop w/ RPV head on (shutting down) (Dd) Mid-loop w/ RPV head off (shutting down)
(6) Mid-loop Operation		
(7) Fill for Refueling		
(8) Refueling	(5) Refueling cavity is filled with water (6) No fuel in the core, or the core is partially offloaded (7) Refueling cavity filled (refueling)	(E) Cavity Flooded (fuel off load) (F) Core Off-load (E) Cavity Flooded (fuel onload)
(9) Draining the RCS to Mid-loop After Refueling	(8) RHR cooling (mid-loop operation)	(Du) RHR: Mid-loop w/ RPV head off

(10) Mid-loop Operations After Refueling		(starting up after refueling) (CBu) Mid-loop w/ RPV head on (starting up after refueling)
(11) Refill RCS Completely (After Mid-loop Operation)		
(12) RCS Heatup Solid and Draw Bubble	(9) RHR cooling (RCS full) (10) RCS leakage test (RHR isolated) (11) RHR cooling (RCS full)	(CAu) RHR: RCS Normal Level (starting up after refueling)
(13) RCS Heatup to 350°F		
(14) Startup with Steam Generators	(12) Hot standby condition	(B) Hot Standby (T > 248°F) (**)
(15) Reactor Startup and Low Power Operation	(13) Low power operation	(A) Power Operation (**)
Notes: (*) APWR POS 1 and 2 are analyzed with the at-power model. (**) EPR POS A and B are analyzed with the at-power model.		

2.2 POS Grouping

The POS defined for the next-generation NPP PSA must represent all conditions that can occur over the course of a fuel cycle. This document considers all plant conditions except full power operation which is addressed with the internal events PSA. The POS, therefore, represent the process or cycle from the reduction for power operation to refueling and back to power operation.

The POS for forced outages are subsets of those for a refueling outage. Furthermore, no unique plant conditions are expected for a forced outage that would not occur during a refueling outage. For example, a reactor trip will take the plant directly from power operation to hot standby bypassing low power operations on entry to the forced outage. From hot standby, the plant may be restarted or it may be cooled and depressurized further. If the plant is restarted, then forced outage will only involve two POSs. Although it may be argued that the decay heat load will be higher in hot standby following a reactor trip than after a planned shutdown, this difference is of negligible consequence. Some forced outages may take the plant down to cold shutdown for work which does not impact the reactor coolant system (RCS) pressure boundary. Other forced outages may require that the RCS pressure boundary be opened. Regardless of whether the RCS is maintained intact or not, all plant conditions that occur during a forced outage also occur during a refueling outage.

The duration of forced outages typically is shorter than refueling outages. Although past practices resulted in forced outages being significant contributors to plant unavailability, recent operating experience with existing reactors shows a very small contribution of forced outages to plant unavailability. In addition, improvements in design are expected to further reduce forced unavailability. With short duration of refueling outages expected for advance design reactors, the duration of any POS is the important consideration. Because the next-generation NPPs are under the design or construction stage, the length of any POS is postulated based on generic practices. Since the overall time spent in any outage is expected to be short for the next-generation NPPs design and since all plant conditions that are expected during forced outages are also expected during refueling outages, risk during forced outage is considered bounded by the risk of refueling outages and separate POS and analyses are not required for forced outages.

Development of POS groups plant states that require similar equipment, timing, and operator actions to respond to an upset condition. Groupings reflect Technical Specification (TS) requirements as well as key factors associated with the main shutdown risk contributors such as RCS temperature, RCS pressure, RCS inventory, State of RCS pressure boundary (vented or intact), Decay heat levels, and draining the RCS.

The POS scope Table 1 represents a reasonable division of potential states for use in LPSD PSAs. Some states could arguably be grouped together without losing resolution. On the other hand, the drain-down evolution can reasonably be divided into two states, one with and one without the

pressurizer manway open, reflecting the presence of an open vent during drainage. However, the particular grouping is determined based on the expected conduct of plant outages and specific thermal-hydraulic features unique to a specific design.

The NUREG/CR-6144 analysis provides reasonable set of POS on which to base a LPSD PSA. These POS have been used as the basis for several industry analyses with little variation. The next-generation NPPs POS groupings will be based on those of NUREG/CR-6144. Details of the next-generation NPPs specific POS definition are provided.

2.3 Identification of Plant Operating States

The POSs defined for the next-generation NPP PSA are based on the 15 POSs defined in NUREG/CR-6144 with adjustments made to account for plant specific design feature. In addition, use of the POS defined in NUREG/CR-6144 is consistent with other recent analyses as summarized in Table 1.

The POSs defined for the next-generation NPP are segregated into two broad categories based on decay heat levels: high decay heat and low decay heat. High decay heat is when the reactor core contains only spent fuel, i.e., from shutdown before defueling. Low decay heat is when the reactor core contains some new fuel, i.e., from commencement of core reload to reactor restart.

Further distinction between POSs is based on the equipment available and needed to mitigate an accident sequence initiated while in each POS. For example, if the RCS is intact, use of feed and bleed cooling requires opening of valves to provide a vent path. However, if the RCS is not intact and the opening provides for adequate flow, then feed and bleed cooling can be accomplished without operator action to open valves.

The shutdown POSs for the next-generation NPP PSA are summarized in Table 2.

Table 2. The Plant Operating States for next-generation NPP

<table>
<tr><th>POS</th><th>Description</th><th>Primary System Water Level (1)</th><th>Primary System Pressure & Temperature</th><th>TS Mode</th></tr>
<tr><td>1</td><td>Reactor trip and Subcritical operation</td><td rowspan="4">In Pressurizer</td><td>2250 psia;
548-585°F</td><td>1, 2</td></tr>
<tr><td>2</td><td>Cooldown with Steam Generators to 350°F</td><td>2250-450 psia;
548–350°F</td><td>3</td></tr>
<tr><td>3A</td><td>Cooldown with Shutdown Cooling System to 212°F</td><td>450-15 psia;
350–212°F</td><td>4</td></tr>
<tr><td>3B</td><td>Cooldown with Shutdown Cooling System to 140°F</td><td>450-15 psia;
212–140°F</td><td>5</td></tr>
<tr><td>4A</td><td>Reactor Coolant System draindown (pressurizer manway closed)</td><td rowspan="4">Below Reactor Flange</td><td>Slight positive pressure or depressurized; <140°F</td><td>5</td></tr>
<tr><td>4B</td><td>Reactor Coolant System draindown (manway open)</td><td rowspan="3">Depressurized;
<140°F</td><td>5</td></tr>
<tr><td>5</td><td>Reduced Inventory operation and nozzle dam installation</td><td>5</td></tr>
<tr><td>6</td><td>Fill for refueling</td><td>6</td></tr>
<tr><td>7</td><td>Offload</td><td>Cavity flooded</td><td>6</td></tr>
<tr><td>8</td><td>Defueled</td><td>N/A</td><td>N/A</td><td>Defueled</td></tr>
<tr><td>9</td><td>Onload</td><td>Cavity flooded</td><td rowspan="2">Depressurized or slight vacuum during refill;</td><td>6</td></tr>
<tr><td>10</td><td>Reactor Coolant System draindown to Reduced Inventory</td><td>Below Reactor Flange</td><td>6</td></tr>
</table>

POS	Description	Primary System Water Level (1)	Primary System Pressure & Temperature	TS Mode
	after refueling		<140°F	
11	Reduced Inventory operation with steam generator manway closure			5
12A	Refill Reactor Coolant System (pressurizer manway open)			5
12B	Refill Reactor Coolant System (manway closed)		Depressurized, or at a slightly elevated pressure; <140°F	5
13	Reactor Coolant System heat-up with Shutdown Cooling System isolation at 350°F	In Pressurizer	15-450 psia 140–350°F	4
14	Reactor Coolant System heat-up with steam generators		450-2250 psia; 350–548°F	3
15	Reactor startup		2250 psia; 548-585°F	2, 1
(1) When level changes during a POS, the minimum level is listed.				

For the next-generation NPP, the plant operational parameters of 15 POSs are identified as follows;

- 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 part (i.e., pressurizer manway, SG manway, pressurizer vent valves, the heat 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 Plant.

It is assumed that the planned outage of the next-generation NPP is basically similar to that of reference plant as the same design concept of PWR. Thus, LPSD PSA of the next-generation has used the procedures and POSs reflected the experiences of the planned outages of reference plants.

The plant arrangements and RCS states are assumed as the same for each POS. The first 7 POSs from POS 1 to POS 7 show the progression of shutdown operation modes and before refueling process. The remained 7 POSs from POS 9 to POS 15 show the progression of the startup operation modes after refueling process. POS 8 shows defueled process.

2.4 POS Classification

Characterization according to the POS classification factors such as refueling, RCS status, and Containment status have been identified as follows:

Table 3. The POS Classification for the next-generation NPPs LPSD Level 1

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 ≤ 99℃) 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 > 99℃) 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		

Conclusions

For the purpose of the development of LPSD Level 1 PSA of the next-generation NPP, POSs have been classified. This is based on the data of operating NPP and certified or under review for next-generation NPPs. The POSs for each of the studies are similar but each has been reclassified according to the TS requirements as well as key factors associated with LPSD risk contributors.

The POSs for the next-generation NPP have been classified into 15 POSs in total. By developing PSA Level 1 during outage according to the POSs for the next-generation NPP, it is possible to develop appropriate and reasonable risk assessments for LPSD.

References

[1] Evaluation of Potential Severe Accidents During Low Power and Shutdown Operations at Surry, Unit 1, NUREG/CR-6144 (BNL-NUREG-52399), June 1994.

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[5] NUMARC 91-06, “Guidelines for Industry Actions to Assess Shutdown Management,” December 1991.