Development of Shutdown PSA Model for Daya Bay NPP

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1、Introduction

- the level 1 shutdown PSA for Daya Bay NPP (DBSD) is based on the same methodology as used for power operation states except for defining different Plant Operational States (POS).
- shutdown PSA model for Daya Bay NPP includes:
  - 27 systems analyzed;
  - 9 groups or 74 initiating events;
  - 74 event trees;
  - 700 accident sequences that lead to a core damage (CD) ;
- total core damage frequency for DBSD is 5.02E-6/ry .
- Development of Risk Monitor for shutdown operation is still under way.

2、SCOPE

- Generally (for plants where refuelling is carried out off-line), there are three different types of outages as follows:
  - Regular refuelling outages. During this period, major maintenance activities are also carried out;
  - Planned outages where only specific maintenance activities are carried out;
  - Unplanned but foreseeable outages which follow a disturbance during full power operation.
- one key difference lies in whether plants will enter mid-loop condition.
- this version of DBSD just focused on non mid-loop condition refuelling outages.

3、Defining Plant Operational States

- With reference to ANS LPSD PRA standard , DBSD's POSs were defined in accordance with the following principles:
  - Definition of POSs should be consistent with those requirements of Technical Specification, one POS should not span two or more RCS Technical Specification mode of operation.
  - Heat removal mechanism and RCS water level are main characteristics taken credit in defining POSs. In each POS, same heat removal mechanism and stable or nearly stable RCS water level are required.
  - POSs shall be defined in a manner that facilitates PSA applications.

Definition of DBSD's POSs

Pos	Description	Plant State			Heat Removal	Starting Point		End Point
		Water Level	Temp. /℃	Pressure / MPa				
POSB	Hot shutdown	IN PZR	284≤T≤294.4	13.9≤P≤15.5	SG，AFW	↓	entering hot shutdown	End of hot shutdown
						↑	entering hot shutdown	Reactor critical
POSC	Intermediate Shutdown (SG cooling, w/o including hot shutdown)	IN PZR	160≤T≤284	2.4≤P≤13.9	SG，AFW	↓	End of hot shutdown	RHR line in
						↑	RHR isolated	entering hot shutdown
POSD	Intermediate Shutdown (RHR cooling)	IN PZR	10≤T≤180	0.5≤P≤3.0	RHR，SG backup	↓	RHR line in	entering MCS
						↑	Departure from MCS	RHR isolated
POSE	MCS (manhole closed)	PZR full	10≤T≤60	0.1≤P≤0.5	RHR，SG backup	↓	Entering MCS	PZR manhole open
						↑	PZR manhole closed	Departure from MCS
POSF	MCS (manhole open)	PZR level+2m→Rx flange level →Rx cavity flooded	10≤T≤60	0.1	RHR，PTR backup	↓	PZR manhole open	Rx cavity flooded
						↑	Starting of draining RCS	PZR manhole closed

PTR: spent fuel pool cooling system ; MCS: maintenance cold shutdown;

" ↑ ": denotes RCS heating up ; " ↓ ": denotes RCS cooling down .

4、Identifying Initiating Events

- Initiating events (IEs) list of DBSD was derived from screening and combination of the following sources:

- IEs listed in ANS LPSD PRA standard;
- IEs listed in other NPPs' PSA reports (e.g., Maanshan PSA report (Taiwan); EPS900; CNP1000);
- Plant-specific designs and practices of Daya Bay NPP .

IEs versus POSs (part 1)

IE Group	IE description	POSB	POSC	POSD	POSE	POSF
LOCA	LLOCA	√	√			
	MLOCA	√	√			
	SLOCA	√	√			
	ISLOCA	√				√
	LLOCA in RHR			√	√	
	MLOCA in RHR			√	√	
	SLOCA in RHR			√	√	√
	Maintenance-induced LOCA (can be isolated)			√	√	√
	Maintenance-induced LOCA (can not be isolated)			√	√	√
Special Initiators	Low Temperature Over Pressure			√	√	
SGTR events	MSLB+SGTR	√				
	SGTR	√				
Loss of RHR	Loss of Running Train of RHR			√	√	√
Transients	Loss of Running Train of AFW	√	√			

IEs versus POSs (part 2)

IE Group	IE description	POSB	POSC	POSD	POSE	POSF
Loss of Offsite Power		√	√	√	√	√
Loss of Supporting System	Loss of Essential Safety-related Power Supply (Train A)			√	√	√
	Loss of Essential Safety-related Power Supply (Train B)			√	√	√
	Loss of CCW/SW	√	√	√	√	√
Reactivity Insertions	Symmetrical Boron Dilution				√	√
	Non-symmetrical Boron Dilution	√				
Secondary Side Pipe Break	Large Main Feedwater Pipe Break	√	√			
	Small Main Feedwater Pipe Break	√	√			
	Large Steam Line Break Inside Containment	√				
	Large Steam Line Break Outside Containment	√				
	Small Steam Line Break Inside Containment	√				
	Small Steam Line Break Outside Containment	√				

5、Human Reliability Analysis

- The Standardized Plant Analysis Risk (SPAR-H) method was developed to support development of plant-specific PSA models for USNRC. It's a simple HRA method for estimating the human error probabilities associated with responses to initiating events. There are mainly four characteristics as follows on its applicability:
  - applicable to evaluate pre-initiator events, post-initiator events and events related to initiating events as well ;
  - capable of quantifying probability of diagnosis failures and action failures. And the process of quantification is relatively simple ;
  - provides HRA process, data and approach specific for shutdown conditions;
  - provides a method to address dependency .
- SPAR-H is selected as the unique HRA method for DBSD.

6、Data Analysis

- DBSD Used the same reliability data as those used in Daya Bay NPP's level 1 PSA for power operations. And frequencies of IEs are derived from:
  - generic data;
  - calculations through fault trees ;
  - the latest 6 years' operational events .
- In DBSD, there are two kinds of unavailability:
  - Test and maintenance unavailability caused by routine work ;
  - Equipment unavailability due to outage .

Unavailability of Essential Safety-related Equipments versus POSs (part 1)

Equipment	POSB	POSC	POSD	POSE	POSF
HPSI001PO	available	available	available	available	available
HPSI 002 PO	available	available	available	available	available
HPSI003PO	available	available	available	availability（47.3%）	availability（58.8%）
Charging line	available	available	available	available	available
7000ppm boron loop	available	available	unavailable	unavailable	unavailable
RHR 001 PO	/	/	available	available	available
RHR 002 PO	/	/	available	available	available
9RIS 011 PO	available	available	available	available	available
LLS 001 TC	available	Partially available	unavailable	unavailable	unavailable
LPSI 001 PO	available	available	available	availability（47.3%）	availability（58.8%）
LHSI 002 PO	available	available	available	available	available
Accumulatot-#1	available	Partially available	unavailable	unavailable	unavailable
Accumulatot-#2	available	Partially available	unavailable	unavailable	unavailable
Accumulatot-#3	available	Partially available	unavailable	unavailable	unavailable
CS 001 PO	available	available	available	availability（47.3%）	availability（58.8%）
CS 002 PO	available	available	available	available	available

Unavailability of Essential Safety-related Equipments versus POSs (part 2)

Equipment	POSB	POSC	POSD	POSE	POSF
CCW 001 PO	available	available	available	available	available
CCW 003 PO	available	available	available	available	available
CCW 002 PO	available	available	available	available	available
CCW 004 PO	available	available	available	available	available
SW 001 PO	available	available	available	available	available
SW 003 PO	available	available	available	available	available
SW 002 PO	available	available	available	available	available
SW 004 PO	available	available	available	available	available
AFW 001 PO	available	available	available	available	availability（58.8%）
AFW 002 PO	available	available	available	available	available
AFW 003 PO	available	available	unavailable	unavailable	unavailable
AFW001BA	available	available	available	available	available
PTR 001 PO	/	/	/	/	available
PTR 002 PO	/	/	/	/	available
SG1	available	available	available	available	unavailable
SG2	available	available	available	available	unavailable
SG3	available	available	availability（76.7%）	availability（39.2%）	unavailable

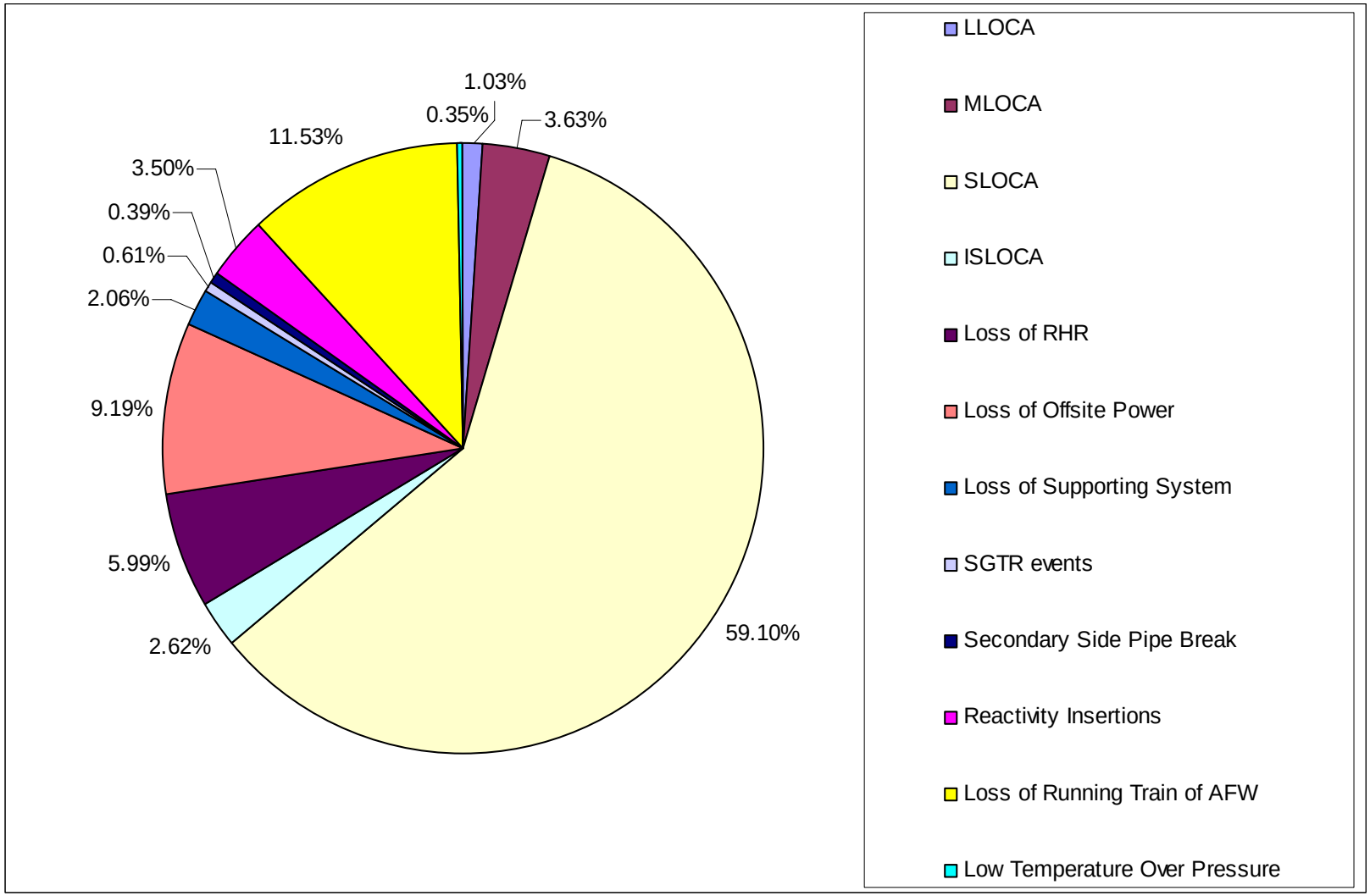
Unavailability of Essential Safety-related Equipments versus POSs (part 3)

Equipment	POSB	POSC	POSD	POSE	POSF
Main steam bypass valve-SG1 (to atmosphere)	available	available	available	available	unavailable
Main steam bypass valve-SG2 (to atmosphere)	available	available	available	available	unavailable
Main steam bypass valve-SG3 (to atmosphere)	available	available	availability（76.7%）	availability（39.2%）	unavailable
Source range neutron flux channel	available	available	available	available	available
Boron meter	available	available	available	available	available
MSIV	unavailable	unavailable	unavailable	unavailable	unavailable
Main transformer	available	available	available	available	available
6.6kV AC emergency power-train A	available	available	available	available	available
6.6kV AC emergency power-train B	available	available	available	available	available
EDG-train A	available	available	available	available	available
EDG-train B	available	available	available	available	available
Auxiliary transformer (offsite power)	available	available	availability（64.8%）	available	available
125V DC-train A	available	available	available	available	available
125V DC-train B	available	available	available	available	available

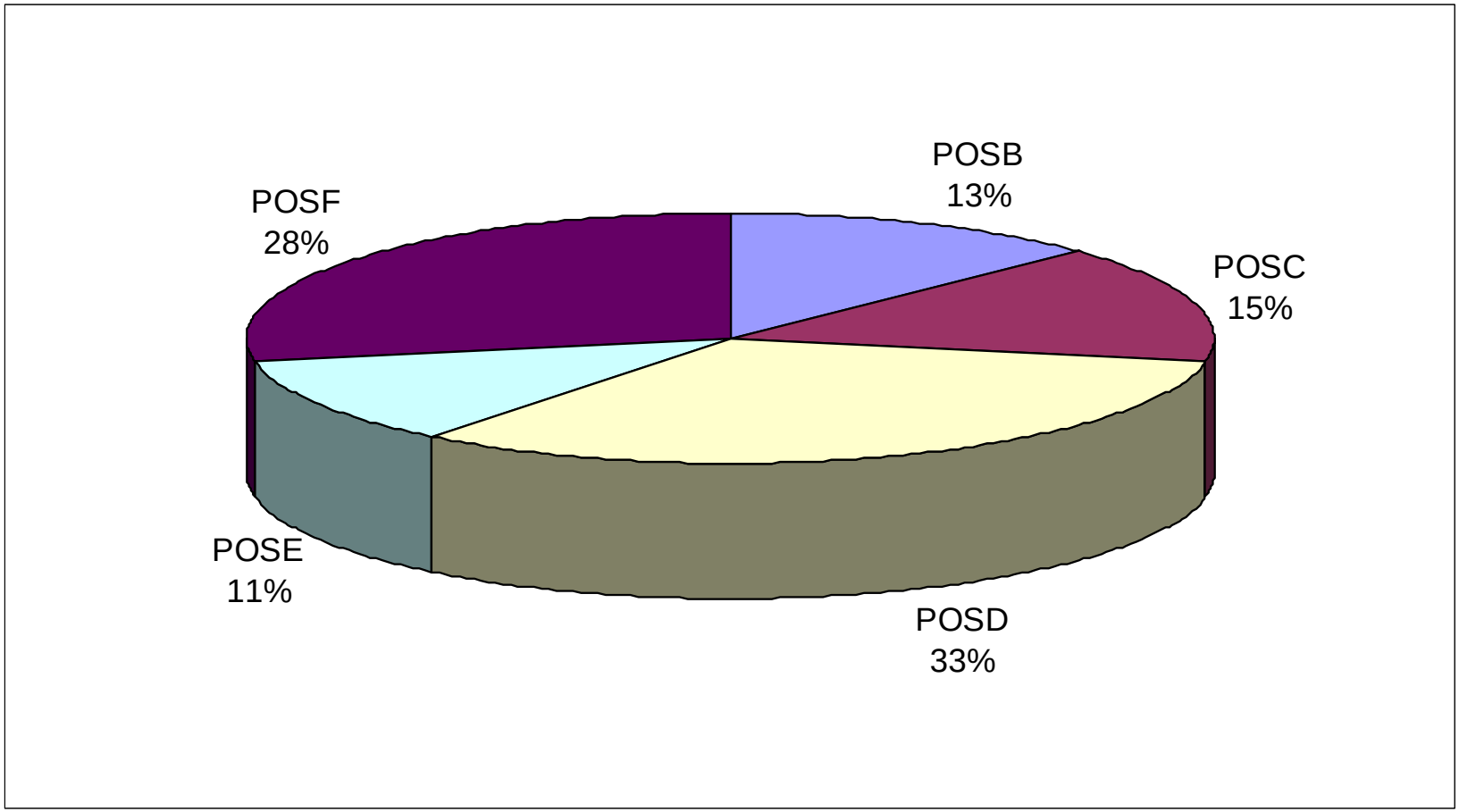
7、Results

- Distribution of CDF per IEs;
- Distribution of CDF per POSs;
- Daya Bay NPP's CDF for shutdown operations versus IEs and POSs;
- Top 5 CD Sequences.

Distribution of CDF Per IEs



Distribution of CDF Per POSs



Daya Bay NPP's CDF for shutdown operations versus IEs and POSs

IE		POS					Total (1/ry)		Proportion (%)	
		B	C	D	E	F				
LOCA	LLOCA	1.80E-09	1.34E-09	4.90E-08			5.21E-08	3.35E-06	1.03%	66.38%
	MLOCA	1.11E-08	1.43E-08	1.57E-07			1.83E-07		3.63%	
	SLOCA	2.35E-08	5.60E-07	6.26E-07	4.48E-07	1.32E-06	2.98E-06		59.10%	
	ISLOCA			1.32E-07			1.32E-07		2.62%	
Loss of RHR (loss of running train of RHR)				2.32E-07	6.20E-08	8.06E-09	3.02E-07		5.99%	
Loss of Offsite Power (LOOP and SBO)		2.39E-08	1.01E-08	4.00E-07	2.00E-08	9.54E-09	4.64E-07		9.19%	
Loss of Supporting System		7.70E-09	3.27E-09	2.63E-08	7.02E-09	6.00E-08	1.04E-07		2.06%	
SGTR Events		3.07E-08					3.07E-08		0.61%	
Secondary Side Pipe Break		1.72E-08	2.34E-09				1.95E-08		0.39%	
Reactivity Insertions		1.48E-07			2.20E-08	6.85E-09	1.77E-07		3.50%	
Loss of Running Train of AFW		4.17E-07	1.64E-07				5.82E-07		11.53%	
Low Temperature Over Pressure				1.40E-08	3.81E-09		1.78E-08		0.35%	
Total		6.47E-07	7.56E-07	1.64E-06	5.63E-07	1.41E-06	5.02E-06		100.00%	

Top 5 CD Sequences

Amongst 700 CD sequences, the top 5 in frequency are listed below:

- BY1F-S05 $F_{BY1F-S05}$=6.40E-7/ry
  Sequence：BY1F*C04*BY1FH1
  BY1F：Initiating Event，Maintenance-induced LOCA (can be isolated) in POSF
  C04：automatically making up water to RCS in case of failure of both RHR pumps
  BY1FH1：manual action about making up water to RCS
- BY1F-S04 $F_{BY1F-S04}$=6.09E-7/ry
  Sequence：BY1F*C04*C02*L01
  BY1F：Initiating Event，Maintenance-induced LOCA (can be isolated) in POSF
  C04：automatically making up water to RCS in case of failure of both RHR pumps
  C02：making up water to RCS
  L01：low pressure direct safety injection

Top 5 CD Sequences (Contd.)

- BS1C-S22 $F_{BS1C-S22}$=3.93E-07/ry
  Sequence：BS1C*BS1CH1
  BS1C：Initiating Event，SLOCA in POSC
  BS1CH1：actuating safety injection manually according to EOP
- SW2B-S10 $F_{SW2B-S10}$=3.83E-07/ry
  Sequence：SW2B*SW2BH1*SW2BH2
  SW2B：Initiating Event，Loss of running train of AFW in POSB
  SW2BH1：RCS cooling down by SG after recovery of main feedwater
  SW2BH2： RCS feed-bleed
- BY1E-S12 $F_{BY1E-S12}$=3.08E-7/ry
  Sequence：BY1E*BY1EH0*L02*H03
  BY1E：Initiating Event，Maintenance-induced LOCA (can be isolated) in POSE
  BY1EH0：Field maintenance personnel correcting mistaken actions
  L02： low pressure direct safety injection
  H03：high pressure direct safety injection

8、Conclusion

- Although there exist conservatives in addressing some technical elements of DBSD, the results are acceptable up to now and the model can facilitate risk management in shutdown operations and help schedule staff to optimize the outage schedule. If plant's practices show that the result of some certain configuration is too conservative, or if the plant will enter mid-loop condition in next refuelling outage, this version of shutdown PSA model shall be updated and enhanced.
- DBSD plays a complementary role on shutdown risk management at this stage.

Thank you for your attention!