PRA Insights Used for SBO Mitigation in Barakah Nuclear Power Plant – Lessons Learned from the Fukushima Accident

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Abstract: After the Fukushima Daiichi Accident in March 2011, Emirates Nuclear Energy Corporation (ENEC) organized a Safety Review Task Force (SRTF) led by its Deputy Chief Nuclear Officer to obtain, evaluate and recommend the implementation of applicable lessons learned to enhance safety features of Barakah Nuclear Power Plant (BNPP). The safety review focuses on beyond design basis accidents (BDBA) and adopts both deterministic and probabilistic approaches to conduct the review. The review results show a high level of plant robustness for BNPP. There have been no design deficiencies identified regarding provisions currently provided to accommodate potential natural hazards, loss of electrical power and loss of ultimate heat sink as well as severe accident management. However, design features for further enhancement of the robustness based on the lessons learned from Fukushima accident have been identified and will be implemented in BNPP. In this paper, a specific Probabilistic Risk Assessment (PRA) study performed to obtain risk insights due to a prolonged SBO event is described. The general approach of how to use the PRA insights to improve nuclear safety is also discussed in the paper. Design improvements based on the PRA application result in a 34% risk reduction in terms of Core Damage Frequency (CDF).

Keywords: PRA, Core Damage Frequency, risk insights, SBO

Introduction

Risk insights obtained from BNPP PRA model has been used to complement BNPP design, which is one of the Fukushima SRTF action items and is also required by the regulation in UAE. A specific sensitivity study regarding risk insights due to an SBO that is the dominant risk for BNPP has been performed. Potential risk management actions based on the risk insights are identified and the effectiveness of each identified action is calculated in terms of CDF reduction. Risk informed decision making process that focuses on risk reduction as well as consideration of budget/schedule impact is performed to determine the final design changes. These design changes result in significantly improving BNPP nuclear safety and will be implemented in BNPP during the construction phase.

Plant Design Futures for SBO Event

BNPP is being constructed on the Barakah site located in the western region of the Emirate of Abu Dhabi, United Arab Emirates. Each of the units will be an advanced design two-loop pressurized water reactor. The Nuclear Steam Supply System (NSSS) is designed for an output of 4,000 MWt. The electrical output from the turbine generator is approximately 1,390 MWe. The design of the BNPP is based on the design of the Shin-Kori Nuclear Power Plant Units 3 and 4 (SKN 3&4) currently being built in the Republic of Korea.

Each unit has two onsite Emergency Diesel Generators (EDGs) to supply emergency power in the event of a Loss of Offsite Power (LOOP). In addition, an Alternate AC (AAC) source consisting of a non-Class 1E diesel generator can be used as a common AC source for the four units (BNPP 1, 2, 3 and 4) to cope with Station Blackout (SBO) scenarios. The Class 1E system consists of four channels of 125 V batteries per unit. Battery Channel C and D are sized to supply power to each channel of loads for two hours without load shedding and six additional hours with load shedding.

Even in the case of a loss of all AC power supplies, 125 V DC batteries will supply electric power for the instrumentation and control system for at least eight hours. In this period the turbine driven Auxiliary Feedwater (TDAFW) pumps are operable, and Natural Circulation Cooldown (NCC) operation can continue to remove decay heat and maintain the plant in a safe shutdown condition.

SBO Accident Sequences

SBO event is initiated by Loss of Off-site Power (LOOP) with concurrent failure of both emergency Diesel Generators (EDGs). The alternate AC (AAC) source can be used to cope with SBO scenarios. If AAC failed after SBO, Reactor Coolant Pump (RCP) seals might fail due to loss of seal cooling that could result in core damage. On the other hand, if RCP seals remain intact, the Turbine Driven Auxiliary Feedwater system (TDAFW) should be available to remove decay heat, and keep Natural Circulation Cooldown. Since the operation of TDAFW requires DC power from battery, if AC power recovery has failed before batteries being depleted, core damage could start. The two SBO accident sequences are shown below:

1. *LOOP – EDGs failed – AAC failed – RCP seal LOCA – Core Damage*
2. *LOOP – EDGs failed – AAC failed – (RCP seals intact) – TDAFW unavailable – Fail to recover offsite power – Core Damage*

For the first SBO sequence, with loss of all AC power, there is no RCP seal cooling water available, which could result in a RCP seal LOCA. Since there is no system available due to loss of AC power to makeup RCS inventory, it could result in core damage.

For the second SBO sequence, 125 V DC batteries with procedural load shedding management could supply power to instrumentation and control system of TDAFW for at least eight hours. NCC operation could continue to maintain the plant in a safe shutdown condition. If AC power could not be recovered before depletion of the batteries core damage is expected to happen.

PRA Insights for SBO

The Level 1 portion of the preliminary Barakah NPP PRA addresses the internal initiators of accident sequences which lead to core damage from a full power operating condition. The level 1 PRA result shows that SBO is the dominant initiating event to core damage, which contributes 48% of the total core damage frequency (CDF). The dominant accident sequence is also from SBO with 45.8% contribution to the CDF. This sequence is initiated by a loss of offsite power followed by failure of both EDGs and AAC DG including common cause failure (CCF), successful delivery of feedwater to the steam generator, no RCP seal LOCA, and failure to recover offsite power within 9.5 hours, as:

LOOP – EDGs failed – AAC failed – TDAFW unavailable due to battery depletion – Failure of offsite power recovery – Core damage

Note: this is the second SBO sequence described in the previous section. The first SBO sequence has much lower contribution to CDF because of low probability of the RCP seal LOCA.

The PRA insights for SBO are summarized as:

- SBO is the dominant contributor to CDF
- The significance of the CCF between EDGs and AAC DG, which have similar designs
- The importance of the RCP seal survivability after loss of seal cooling
- The importance of offsite power recovery after SBO. The probability of offsite power recovery is dependent on the time available for the recovery, which is closely related to the battery life

Risk Management Approach

In order to effectively manage the SBO risk, the following approach has been accepted to develop risk management actions:

- Identify potential risk management actions based on PRA insights to prevent and mitigate SBO event
- Assess the impacts in terms of CDF reduction if those risk management actions being implemented
- Apply risk–informed decision making that weights risk reduction and financial impact to determine specific design changes and risk management actions

There are 8 potential risk management actions have been identified to prevent and mitigate SBO event. These potential risk management actions are:

No.	Items	Reason
1	Reduction of common cause failure between EDGs and AAC DG	Increase the reliability of AC power after LOOP event
2	Additional AAC DG (two AAC DG for 4 units)	Increase the reliability of AC power after LOOP event
3	Add one mobile DG on BNPP site	Provide additional AC power for safe shutdown function after SBO event
4	Battery life extension from 8 hours to 16 hours	Prolong safe shutdown function from 8 hours to 16 hours after SBO, and increase probability for offsite power recovery
5	RCP seal LOCA prevention	Maintain RCS inventory integrity and to prevent LOCA after SBO
6	Provision of EDG unit cross-tie	Provide additional AC power for safe shutdown function after SBO event
7	Provisions of maintainability of off-site power or EDG recovery (procedure, training and facility)	Increase probability to recover AC power after SBO
8	Improvement of equipment reliability such as EDGs, AAC DG and AFTDPs (Maintenance Rule implementation)	Increase the reliability and availability of AC power sources as well as the secondary heat removal function

A PRA sensitivity study is performed to assess risk reductions with financial impact if the identified risk management actions would be implemented.

Case No.	SBO Prevention/Mitigation	Risk Reduction (%)		Cost Impact (H, M and L)
		CDF*	LERF**	
1	Reduce the CCF between EDG and AAC DG (assume dependency reduced by 50%)	14	15.1	M
2	Additional AAC DG with larger fuel tank	10	10.0	H
3	1 Mobile DG per site	27	27.9	M
4	Battery life extension from 8 hours to 16 hours	28	29.9	M
5	RCP seal LOCA prevention (assume the RCP seal failure rate reduced by 90%)	9	0.3	M
6	EDG Unit crosstie (assume 10% human error probability)	32	32.6	L
7	EDG recovery (assume 20% recovery probability)	7	7.0	L
8	EDG, AAC DG, TDAFW pump reliability improvement – Maintenance Rule implementation (assume reliability improve 20%)	8	8.2	L
9	**Cases 6+4**	**34**	**35.5**	**M**
10	Cases all	43.3	36.3	H

* CDF = Core Damage Frequency

** LERF = Large Early Release Frequency

Other than maintenance practices to reduce CCF between EDG and AAC (case 1), to improve safety system reliability through implementing Maintenance Rule (case 8), and to provide training to maintenance people for EDG recovery (case 7), PRA study shows that the most effective design improvements that balance both risk reduction and financial impact at the plant design/construction stage are: 1) battery life extension (case 4), and 2) EDG unit crosstie (case 6). The additional 8 hours battery life extension significantly improves the probability of offsite power recovery. EDG unit crosstie that has been successfully used in US nuclear industry to meet SBO rule (Ref. 1, 2) (in Fukushima event, power crosstie from unit 6 to unit 5 was implemented) also has a substantial effect to mitigate SBO consequence. It's important to recognize that "unit crosstie" should be used only during a beyond design basis accident – in this case, a prolonged SBO.

PRA insights were input to final decision making (risk-inform decision making process) for SBO risk management. As provisions for increasing robustness of BNPP for the SBO, major improvements of electric power system have been determined and will be implemented before plant operation as follows:

- Channel C & D, Class 1E, battery duty extension from 8 hours to 16 hours
- Unit Cross Tie Design of EDGs and AAC DG for Emergency Power Supply
- Installation of Mobile DG Connection on the outside of the Auxiliary Building
- Extension of Fuel Capacity, of AAC DG Fuel Oil Storage Tank, from 8 hours to 24 hours

Conclusions

The challenge faced in nuclear power industry after the Fukushima event is how to manage risk caused by beyond design basis accidents, especially, for prolonged SBO and Loss of Ultimate Heat Sink (LUHS) events. PRA is a powerful tool to identify risk insights for beyond design basis accidents, which include risk contributions from initiators, components, maintenance activities, common cause failures, and operator actions, more importantly, to identify the dominant accident sequences. Those risk insights can be used to effectively manage risk for beyond design basis accidents. The process of how to use PRA insight to mitigate SBO has been described in the paper and has been successfully applied in BNPP resulting in 34% risk reduction. In order to effectively manage risk for beyond design basis accidents, it is mportant to include PRA insights into a risk-informed decision making process in order to determine specific risk management activities.

References

1. NRC issued the final SBO Rule (10 CFR 50.63) on June 21, 1988
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