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확장된 소내전원 상실 사고시의 대체대응활동 완화를 위한 비교 연구: 시스템 엔지니어링 관점으로

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A Comparative Study on Mitigation Alternatives in Response to an Extended SBO for APR1400 Using Systems Engineering

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Abstract : The safety of nuclear power plants has received much attention; this safety largely depends on the continuous availability of electrical energy source during all modes of nuclear power plant operation. A station blackout (SBO) describes the loss of the off-site electric power, the failure of the emergency diesel generators, and the unavailability of the alternate AC (AAC) power. Consequently, all systems that are AC powered such as the safety injection, shutdown cooling, component cooling water, and essential service water systems are unavailable. The aim of this study is to investigate the deficiencies of the existing alternatives for coping with an extended SBO for APR1400 design. The method is analyzing the existing deficiencies and proposing an optimal solution for the NPP design during the extended SBO. This study, established a new passive system, called passive decay heat removal system (PDHRS), using systems engineering approach.

Key Words : NPP, Alternatives, Systems Engineering, AFWS, PDHRS, PRA

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1. Introduction

The APR1400 is a pressurized light water reactor that has many improvements for safety with thermal power 3983 MWt designed by Korean Hydro and Nuclear Power (KHNP) Company of South Korea. The reactor containment building (RCB) is a cylindrical pre-stressed concrete structure with a hemispherical dome. The reactor coolant system (RCS) is comprised of two primary coolant loops; each loop has two reactor coolant pumps (RCPs), a steam generator (SG), and connected pipes. An electrically heated pressurizer is connected to one of the loops of the RCS, and these equipment are contained in the RCB. The safety injection system (SIS) utilizes four safety injection pumps to inject borated water into the reactor vessel. In addition, four safety injection tanks with the fluidic device are provided to improve the system operability and reliability by regulating the borated water injection rate effectively.

The APR1400 unit has two Emergency Diesel Generators (EDGs) in the auxiliary building, an alternate AC (AAC) power source for loss of offsite power (LOOP) events when the EDGs are out of service, and DC power from the station batteries which will serve for a period of eight hours following a station blackout (SBO). After the Fukushima accident, all Korean nuclear power plants especially APR1400, were subjected to comprehensive special safety inspections to reaffirm the desired response to the extended SBO sequences. The most important action items include securing the availability of portable power generators vehicles, installation of external water injection provision, and equipment to the RCS and SGs.

In respect to SBO, some alternatives for mitigation management have been described in previous papers. These include external water injection for cooling the SGs using portable devices and the operation of motor driven auxiliary feedwater pumps (MD-AFWPs) by portable power generators.

This paper will focus on presenting new passive alternatives using systems engineering (SE) approach, which will have the capability of decay heat removal, safety injection, and containment cooling. These alternatives will be referred to as the passive decay heat removal system (PDHRS).

2. Previous Studies

2.1 Station Blackout Mitigation after Fukushima Dai-Ichi Accident

The SBO is initiated by a loss of off-site power (LOOP) with a concurrent loss of all AC power and loss of ultimate heat sink (LUHS). This results in subsequent loss of active safety systems such as safety injection system (SIS), shutdown cooling system (SCS), essential service water system (ESWS), and component cooling water system (CCWS); the loss of CCWS causes leakage in RCPs seals. The direct current (DC) from station batteries remains the only source to supply the needed control and instrumentation power, for eight hours, during SBO.

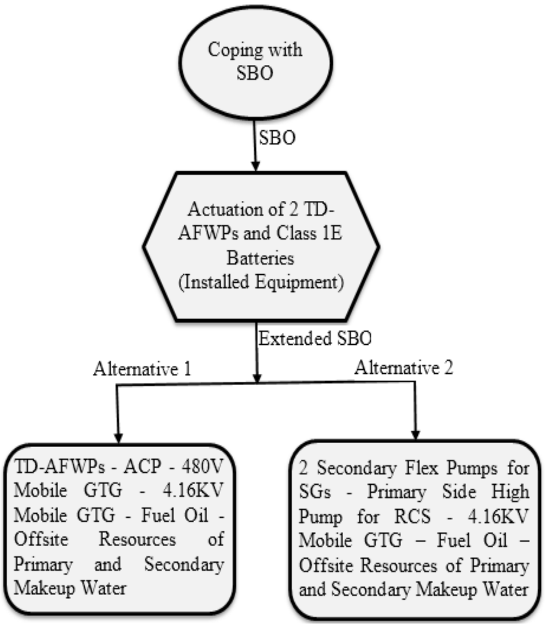
The methodology to establish a baseline coping capability from nuclear energy institute (NEI) was considered in developing the APR1400 FLEX strategy for SBO mitigation management [3]. Each FLEX strategy follows a three-phase approach: initial response phase using installed equipment, transition phase using portable equipment and consumables, and indefinite sustainment of these functions using offsite resources [13].

2.2 SBO during the First Eight Hours

During the first eight hours, only the installed equipment is used. Specifically, TD-AFWPs actuate automatically by the auxiliary feedwater actuation signal (AFAS) for supporting core cooling through the SGs. Auxiliary feedwater storage tanks (AFWSTs) provide the water to the TD-AFWPs, and the steam generated in the SGs is released through the main steam safety valves (MSSVs). The RCP seal leakage is supposed to be 25 gpm per RCP. Class 1E station batteries support DC power source to necessary control equipment, instrumentation equipment, and the operation of the TD-AFWS. Hence, the RCS is kept at hot standby mode by the natural circulation cooldown (NCC) operation without any operator action during this period.

2.3 SBO Alternatives after Batteries Depletion

There are 2 alternatives, one is in the main operational strategy and the other is in the contingency strategy. In the main operational strategy, the RCS is cooled down to the hot shutdown mode by feed and bleed operation using the TD-AFWPs and the atmospheric dump valves (ADVs) through the SGs. The raw water tank (RWT) is considered as a backup water source of the AFWSTs. The auxiliary charging pump (ACP) is used to cool the RCP seals and maintain the RCS inventory by providing makeup water from the boric acid storage tanks (BAST) and in-containment refueling water storage tank (IRWST). Two 480V mobile gas turbine generators (GTGs) supply power to the 125V DC battery charger, the 480V load center, and the motor control center [13].



[Figure 1] Alternatives for SBO mitigation

In the contingency strategy, installed plant equipment is assumed to be inoperable even after connection of the 480V mobile GTG [13]. In this situation, the RCS is further cooled to approximately 210 °F with SGs fed by the secondary FLEX pumps [13]. RCS inventory makeup is accomplished by the primary side high head FLEX pump.

For long-term coping (more than 72 hrs.) with the extended SBO, It is possible to use off-site resources to support the main operational strategy and the contingency strategy, including a 4.16 kV mobile GTG to restore train A or B of the 4.16 kV Class 1E power system, fuel oil for the mobile GTGs, and primary and secondary makeup water sources. Figure 1 summarizes these scenarios.

2.4 The Deficiencies in Current Designs

The current designs for SBO mitigation are mainly dependent on the TD-AFWPs. If the TD-AFWPs fail to deliver feedwater to the SGs, secondary steam removal through the secondary safety valves or atmospheric dump valves (ADVs) will continue until the steam generators boil dry at approximately 40 minutes, which was estimated using MAAP code [6]. Primary pressure rapidly rises and the POSRVs are opened. The core uncovers and core damage will occur unless power is restored and auxiliary feedwater flow is established.

The level 1 PRA of the APR1400 result shows that SBO is the dominant initiating event to core damage, which contributes 39% of the total core damage frequency (CDF). Table 1 presents the event sequences that contribute to core damage frequency (CDF). The contribution to CDF due to SBO event sequences is 3.35E-7 per year [6]. From this table, most of the contributions to CDF result from the failure of the AFWP to deliver feedwater.

Although previous research has established that a strategy using fire trucks could be effective in coping with an extended SBO when the pumps and valves are aligned within 30 min. after severe accidents, but it may take more than 30 min. to be ready for operation.

<Table 1> CDF contributions for SBO core damage sequences

Sequence SBO	EDG	AAC	AFW	Recovery Offsite Power within 40 mins.	Recovery Offsite Power within 10 hrs.	Secondary Heat Removal	Safety Dep. for Bleed	Safety Injection for Feed	CDF Contribution (Events/Year)
1	F	S	S	–	–	F	S	F	9.73E-13
2	F	S	F	–	–	–	S	F	5.75E-11
3	F	S	F	–	–	–	F	–	1.15E-12
4	F	S	F	–	–	–	S	F	4.47E-11
5	F	S	F	–	–	–	F	–	4.65E-11
6	F	F	S	–	S	F	S	F	3.84E-13
7	F	F	S	–	S	F	F	–	1.16E-11
8	F	F	S	–	F	–	–	–	3.18E-07
9	F	F	F	S	–	–	–	–	2.49E-12
10	–	–	F	F	–	–	–	–	1.67E-08
Total									3.35E-07

Most of these alternatives are active systems which need a power source to work. The use of passive systems can eliminate the costs associated with the installation, maintenance, and operation of active systems that require multiple pumps with independent and redundant electric power supplies.

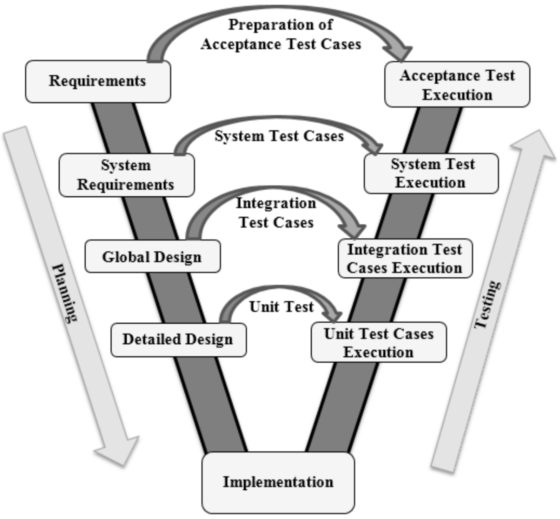
3. Systems Engineering Approach

3.1 Introduction

Based on sub-section 2.2, it is necessary to establish a systems engineering (SE) approach to enhance safety features of APR1400 during SBO and to adopt both deterministic and probabilistic approaches for CDF reduction. The application of passive safety systems that depends on gravity for operation can contribute to, potentially, improve the economics of new NPPs designs.

“Systems engineering (SE) is an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the needs of the customers and stakeholders are satisfied in a high quality, trustworthy, cost efficient, and schedule compliant manner throughout the entire life cycle of a system” [1]. The aim of SE is to specify and design a balanced system that satisfies the needs and requirements of the stakeholders by solving the problem in accordance with the stated need.

“There are different life-cycle models for the system of interest (SOI) such as waterfall, spiral, vee, and agile development models. The most famous model is the vee model which is



[Figure 2] V model of new system for SBO mitigation

used to provide a useful illustration of the SE activities during the life cycle stages, particularly during the concept and development stages" [1].

"The technical processes and supporting process activities are invoked throughout the life cycle stages of SOI" [1]. The technical processes begin with:

1. Requirements: decay heat removal during SBO
2. System Requirements: transfer these needs into more technical requirements of providing feedwater to the SGs using passive system for decay heat removal when AC power is lost. This new system can be applied feasibly to both new and current designs of APR1400.
3. Global Design (Architecture Design): transfer or synthesize these requirements into products or systems to satisfy the needs of the stakeholders. The system description is shown in figure 5 and 6.
4. Detailed Design: realize a specified system element and then assemble the system that is consistent with the architecture design.
5. PDHRS Simulation: connection of this passive system to APR1400 nodalization, and then perform simulation using MARS code to confirm that the specified design requirements are fulfilled by the system and it is able to work in the operational environment [11]. In this process, the testing processes including the unit test cases, integration test cases, system test, and acceptance test executions have done.
6. Finally, confirm that the system delivers its services.

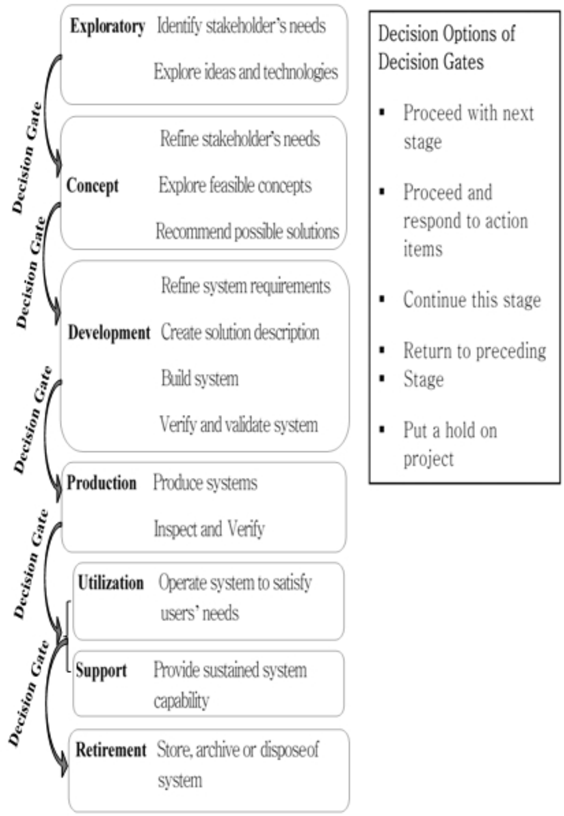
3.2 Life Cycle Stages of System

"The engineering of a new system usually begins with an exploratory stage in which a new system concept is evolved to meet a recognized need or to exploit a technological opportunity. The system life cycle is commonly used to refer to the stepwise evolution of a new system from concept through development and on to production, operation, and ultimately disposal" [7].

"SE applies to all phases of the life cycle, but primary SE activity is concentrated on concept and development stages". The main life cycle stages are shown in figure 3.

4. Implementation of SE Approach for SBO Mitigation

The new system implemented by the SE approach is the passive decay heat removal system (PDHRS). This system consists of two passive decay heat removal tanks (the first one for SGs and the other for reactor vessel), and some valves to control the system. These



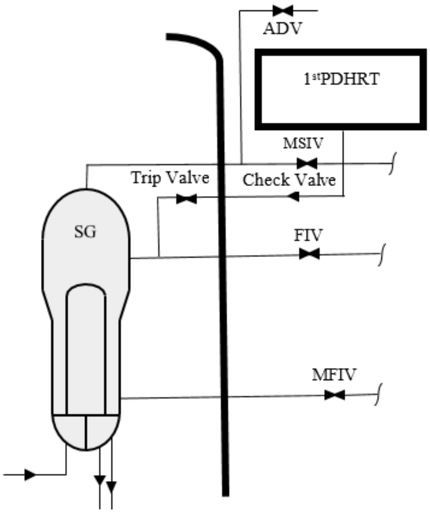
[Figure 3] System life cycle stages

tanks are large, filled with cold borated water, and elevated outside the containment. It uses the concept of injection by gravity.

4.1 The First Passive Decay Heat Removal Tank (1st PDHRT)

The passive decay heat removal system (PDHRS) is generally concentrated on the removal of decay heat, not water level control for avoiding SG overfill. Therefore, although it can cope with DBAs like the loss of feedwater and the loss of condenser vacuum, the initiation of the operation is limited for beyond DBAs (BDBAs) [11].

The PDHRS injects the coolant from the first PDHRT into the SGs using gravity after depressurization and isolation in the secondary loop. The main feedwater isolation valves, main steam isolation valves, and downcomer feedwater isolation valves (FIVs) are closed after the turbine trip.



[Figure 4] The 1st PDHRT for SG

The atmospheric dump valves (ADVs) are opened to reduce the pressure of the SGs during the initiation operation of PDHRS; and thereafter, the trip valve is opened to inject the coolant from PDHRT after reaching the operating pressure. The main objective of the check valves is containment isolation in the case of normal operation and avoidance of countercurrent flow during accidents. The cooling water flows to the SGs from the first PDHRT and is evaporated and delivered to the atmosphere outside the containment through the ADVs. The concept of first PDHRT design for APR1400 is shown in figure 4.

There is a similar actual application of the PDHRS in Angra unit 2 in Brazil. A reservoir of 5000 t of water, located on an elevation 110 m above the site grade, was designed as a fire fighting water supply system [12].

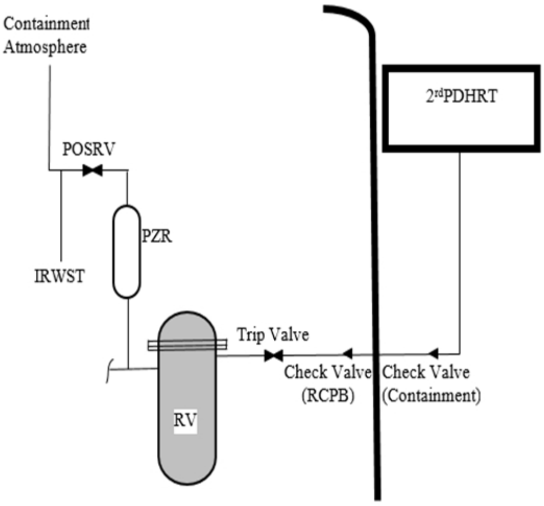
4.2 The Second Passive Decay Heat Removal Tank (2nd PDHRT)

The second PDHRT is to provide the borated cooling water to the reactor pressure vessel during a SBO for RCS inventory makeup. Figure 5 shows the concept of the second PDHRT design for APR1400. There are two check valves on the line connected between the second PDHRT and the reactor vessel. The general objective of check valves is protecting the pressure boundaries and preventing the countercurrent flow of coolant. The first check valve is for isolation of containment in the case of the normal operation mode, and the second is for protecting the integrity of the reactor coolant pressure boundary.

The reactor vessel pressure is first checked before the initiation of the PDHRS. The pilot-operated safety relief valves (POSRVs) on the pressurizer are used for depressurization of the RCS if the reactor vessel pressure is much higher than that for the PDHRS. When the POSRVs are opened, the steam from the pressurizer goes to the in -containment refueling water storage tank (IRWST) or to the containment atmosphere. Thereafter, the operation of the PDHRS is accomplished by opening the trip valve.

4.3 Technical Design Requirements

The coolant from the second PDHRT needs to be injected sufficiently to makeup for the loss in the RCS so as to maintain the water level in the reactor vessel. On the other hand, the coolant of the first PDHRT is used to remove decay heat in the SGs by cooldown of the RCS [11]. Boric acid is stored in the two PDHRTs, which maintains the subcritical state of the core, cools the SGs in case of extreme accidents, and secures sufficient preparation time to recover the AC power [11].



[Figure 5] The 2nd PDHRT for RV

Refilling of the PDHRTs after depletion is accomplished by off-site equipment, dependent on the accident conditions. Every valve in figure 4 and 5 will be arranged as multiple valves in parallel for the actual application. The operator decision to initiate the first PDHRT or the second PDHRT is based on the conditions of the plant. The trip valve is opened by DC power or manual control. There is limited depressurization in the RCS when the DC power also fails. Accordingly, installations of additional batteries to be used for the PDHRS and safety depressurization system (SDS) will increase the availability of the systems [11].

The PDHRS can be applied feasibly to both new and current designs using emergency external injection lines connected to SGs and can be implemented in the APR1400.

5. Results and Conclusions

One of the challenges faced by the nuclear power industry, after the Fukushima Dai-Ichi NPP accident, is how to mitigate sequences caused by BDBA, specifically the extended SBO.

From the studies of the current alternatives for the extended SBO mitigation, the overall coping capability of the APR1400 for this event is summarized as follows: (1) TD-AFW can efficiently cool down the RCS and provide roughly 12 hrs. of additional time for the operator to recover the AC power and prevent core damage. (2) Extension of batteries life can effectively prolong SBO coping time to 72 hrs. (3) An external injection into SGs using flex pumps can be an effective strategy when it is successfully aligned within 30 min.

The use of passive safety systems such as gravity driven safety injection systems (PDHRS) can eliminate the cost associated with the installation, maintenance, and operation of active safety systems that require multiple pumps with independent and redundant electric power supplies [14]. The PDHRS has many design merits, some of which are maintenance and accessibility, even if the conditions surrounding the site are severe [12]. Also the PDHRS can be applied in existing and new NPPs for enhancing the safety features.

6. Conflict of Interests

The authors declare that there is not conflict of interest regarding the publication of this paper.

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References

1. INCOSE Systems Engineering Handbook v. 3.2.2 INCOSE-TP-2003-002-03.2.2 October 2011.
2. Avinash J. Gaikwad, P. K. Vijayan, Sharad Bhartya, Kannan Iyer, Rajesh Kumar, A. D. Contractor, H. G. Lele, S. F. Vhora, A. K. Maurya, A. K. Ghosh, and H. S. Kushwaha, Effect of Coolant Inventories and Parallel Loop Interconnections on the Natural Circulation in Various Heat Transport Systems of a Nuclear Power Plant during Station Blackout, Research Article ID 458316, 2008.
3. Nuclear Energy Institute (NEI 12-06), Rev. 0, Diverse And Flexible Coping Strategies (FLEX) Implementation Guide August 2012.
4. Sang-Won Lee, Tae Hyub Hong, Mi-Ro Seo, Young-Seung Lee, and Hyeong-Taek Kim, Extended Station Blackout Coping Capabilities of APR1400, Research Article ID 980418, 2014.
5. Jongrok Hwang, and Seungjong Oh, Developing Optimal Procedure of Emergency Outside Cooling Water Injection for APR1400 Extended SBO Scenario Using MARS Code, KEPCO International Nuclear Graduate School, 1456-1 Shinam-ri, Seosaeng-myeon, Ulju-gun, Ulsan, Korea, 2013.

6. APR1400 Standard Safety Analysis Report (SSAR).
7. Alexander Kossiakoff, William N. Sweet, Samuel j. Seymour, and Steven M. Biemer, Systems Engineering Principles and Practice, Second Edition, 2011.
8. Systems Engineering Handbook, a Guide for System Life Cycle Processes and activities, Fourth Edition, Incose-tp-2003-002-04, 2015.
9. APR1400 Design Description, 2014 Korea Hydro& Nuclear Power Co., Ltd.
10. IAEA Website, https://www.iaea.org/pris/.
11. Sang Ho Kim, Soon Heung Chang, Yu Jung Choi, and Yong Hoon Jeong, A Passive Decay Heat Removal Strategy of The Integrated Passive Safety System (IPSS) for SBO Combined with LOCA, Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 291, Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea, 13 November 2015.
12. Carneiro, Paulo, 2013. Brazilian nuclear operator's response to Fukushima accident, IAEA Technical Meeting on Evaluation of NPP Design Safety in the Aftermath of the Fukushima Daiichi Accident, 26-29 August 2013, Vienna International Centre.
13. APR1400 Design Document Tier 2, Probabilistic Risk Assessment and Severe Accident Evaluation, Kepco and KHNP Co., Ltd., Revision 0, December 2014.
14. Passive Safety Systems and Natural Circulation in Water Cooled Nuclear Power Plants, IAEA-TECDOC-1624, IAEA, Vienna, 2009.