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Advantages of the AFWS for APR1400 in Response to SBO using MARS Code

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***Abstract*--The APR1400 is an evolutionary pressurized water reactor with an output rating of 1,400 MWe designed by Korea Hydro and Nuclear Power Co., Ltd. APR1400 incorporates a variety of engineering and operational improvements designed to provide additional reliability and safety margins with core damage frequency of less than 1.0E-5/year. The safety of nuclear power plants depends on the continuous availability of electrical power during all modes of NPP operation. The aim of this study is to investigate the use of auxiliary feedwater system response to achieve the best behavior for APR1400 during the first eight hours of a station blackout using MARS code. Our scenario for coping with station blackout is dependent on the feedwater flow rate injected by the turbine driven auxiliary feedwater pumps to the steam generators. In this study, we have obtained the optimum flow rate of feedwater to maintain the plant in a safe hot standby condition.**

Key Words-- NPP, SBO, TD-AFWPs, ADVs, SITs, RCP Seal Leakage

I. INTRODUCTION

A. APR1400 Plant Description

The main design philosophy of the APR1400 is the enhancement of safety by using proven technologies and significant experiences gained in design, construction, maintenance, and operation of NPPs, especially OPR1000 units, in South Korea [2].

The APR1400 is a 3983 MWt pressurized light water reactor designed by a Korean hydro and nuclear power (KHNP) company. 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 as shown in Figure 1. An electrically heated pressurizer (PZR) is connected to one of the loops of the RCS, and these equipment are located within the RCB. The key design parameters of the APR1400 are described in Table 1.

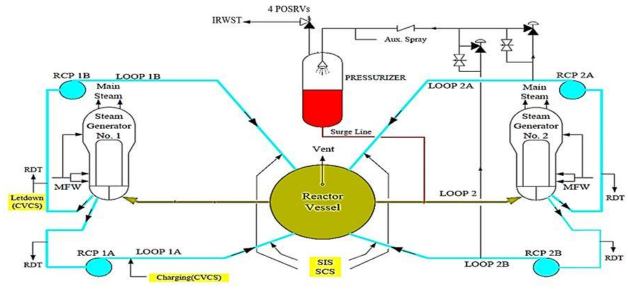

Figure 1: RCS arrangement

The safety injection system (SIS) utilizes four safety injection pumps (SIPs) to inject borated water into the reactor vessel. In addition, four safety injection tanks (SITs) with a fluidic device are provided to improve the system operability and reliability by regulating the borated water injection rate effectively [2]. One of the most important improvements in the APR1400 is its response to a severe accident, the reactor pressure vessel (RPV) exterior surface can be submerged to remove decay heat from the molten debris in the RPV bottom head to prevent RPV thermal failure.

The auxiliary feedwater system (AFWS) of APR1400 is designed to provide a minimum required total flow during transient or accident conditions, especially SBO. This minimum flow is delivered at loss of normal feedwater, any incident which will result in loss of both off-site and normal on-site AC power, or minor secondary system pipe breaks.

Table 1
key design parameters of the APR1400

Parameters	APR1400	MARS Code
Design life (yrs)	60	---
Thermal Power (MWt)	3,983	3,976
Net Electric Power (MWe)	1,400	---
Reactor coolant system (RCS) flow rate (kg/hr)	$75.57*10^6$	$75.5*10^6$
Inlet temperature (^{0}C)	291	290.5
Outlet temperature (^{0}C)	324	325
Operating pressure (kg/cm^2)	158	158.158
Active core height (cm)	381	381
Average linear heat rate (kW/m)	17.53	17.51
Number of fuel assembly	241	241
Fuel assembly lattice	16×16	---
Number of control element assemblies (CEAs)	93	93
Steam Generator (SG) pressure (kg/cm^2)	70.3	70.024
SG tube material	Alloy 690	---

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B. APR1400 Behavior Description during SBO

The APR1400 unit has two emergency diesel generators (EDGs) in the auxiliary building, an alternate AC (AAC) power for loss of off-site power (LOOP) events when EDGs are out of service, and a DC power from station batteries which will serve for a period of eight following SBO. The station batteries supply DC power to essential instrumentation and controls (I&Cs) and to the TD-AFWPs during SBO [3]. This is necessary for monitoring and control the condition of both the SGs as well as the pressurizer (i.e. level, pressure, and temperature), and consequently send a control signal to the AFWS to provide the necessary amount of feedwater to the SGs for decay heat removal during a SBO. Additionally, the DC power is needed by the turbine controller to actuate the TD-AFWPs. Hence, the depletion of the batteries would result in the TD-AFWPs trip due to loss of DC power to the turbine controller [3].

An SBO event means the loss of all AC power sources, which is initiated by a LOOP with the failure of EDGs, AAC power unavailability, and loss of ultimate heat sink (LUHS). Therefore, all active safety systems are not available including SIS, shutdown cooling (SCS), and essential service water systems (ESWS). The component cooling water system (CCWS), used to cool the RCP seals, also is not available which then causes RCP seal leakage. This in turn leads to a small break loss of coolant accident (SBLOCA).

The nuclear reactor is then scrammed following the loss of AC power source and the turbines are simultaneously tripped. Shutdown mode of a NPP requires continuous cooling of the reactor core to remove the decay heat produced from fission products and actinides. This is approximately 7% of the total reactor power at the beginning of shutdown mode. To remove decay heat in the RCS and maintain the plant in a safe hot standby condition during SBO, coolant is circulated by natural circulation cooldown (NCC) and feedwater is provided to SGs by AFWS.

C. AFWS Behavior Response to SBO

The function of the AFWS is to provide adequate cooling water from the auxiliary feedwater storage tanks (AFWSTs) to the SGs in the event of the loss of main feedwater [2]. The AFWS can be actuated manually or automatically by the auxiliary feedwater actuation signal (AFAS). The AFWS consists of two mechanical divisions and each division has two independent auxiliary feedwater trains which are aligned to feed into the respective SG [2]. Each division has one motor- driven auxiliary feedwater pump (MD-AFWP) in the first train and one turbine- driven auxiliary feedwater pump (TD-AFWP) in the second train, as seen in Figure 2.

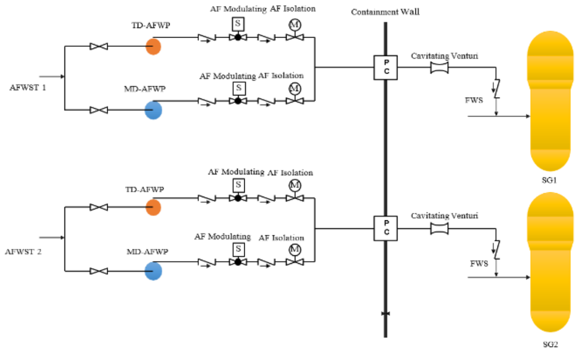

Figure 2: AFWS

Response to SBO, only the TD-AFWPs are available for a limited time which is the batteries life time. The TD-AFWPs are required to supply auxiliary feedwater to the SGs to remove the RCS decay heat, and secondary steam must be removed via the main steam safety valves (MSSVs) or the atmospheric dump valves (ADVs) [3].

With procedural load management, the batteries supply the needed instrumentation and control (I &C) power for eight hours. Initial plant cooldown can occur for eight hours without restoration of AC power [3].

At the beginning of AC power loss, the ADVs will become inoperable, the SG pressure will increase to the secondary safety valve set point, and the primary pressure and temperature will increase until the heat transfer from the RCS to the SGs is in equilibrium with the heat removed from the SGs by the safety valves. The plant would remain stable in this configuration until AC power is restored or the AFWS become inoperable due to the loss of control power as a result of battery depletion. Core damage would follow in about two hours unless water flow to the SGs is re-established [3].

If the TD-AFWPs fail to deliver feedwater to the SGs, secondary steam removal through the ADVs will continue until the SGs boil dry at about 40 minutes, calculated by MAAP code. Primary pressure will rapidly rise and the pilot operated safety relief valves (POSRVs) will open. The core will uncover, and thus core damage will occur unless power is restored and AFW flow is established [3].

D. MARS Code and APR1400 Model Nodalization for SBO

The MARS (Multi-dimensional Analysis of Reactor Safety) code is currently being developed by KAERI for a multi-dimensional and multi-purpose, realistic thermal-hydraulic system analysis of light water reactor transients. MARS development program consists of three stages of code development, the MARS 1.x was developed in 1997 to establish a basic code frame for multi-dimensional thermal-hydraulic system analysis. MARS 2.x was developed as a consolidated code for coupled analysis of multi-dimensional, system thermal-hydraulics; 3-D core kinetics; core CHF; and containment. MARS 3.x has been developed as a multi-purpose code for hydraulic analysis of new types of advanced reactors [1].

The backbone of MARS code is the RELAP5/MOD3.2 and the COBRA-TF codes of USNRC. The RELAP5 code is a versatile and robust system analysis code based on a one-dimensional, two-fluid model for two-phase flows; whereas, the COBRA-TF code is based on a three-dimensional, two-fluid, three-field model. The two codes were consolidated into a single code by integrating the hydrodynamic solution schemes, and unifying various thermal-hydraulic models [1].

Figure 3 shows the nodalization diagram of the APR1400 MARS model. The calculated results from MARS code, in the steady state, were validated with the key design parameters in Table 1. The nodalization diagram is modeled for the required components for APR1400 during SBO, which contains the reactor vessel, 2 hot legs, 4 cold legs, 4 RCPs with its leakage seal, 2 SGs, PZR, surge line pipe, auxiliary feedwater lines, main steam lines, safety injection tanks (SITs) with their fluidic devices, and atmospheric dump valves (ADVs).

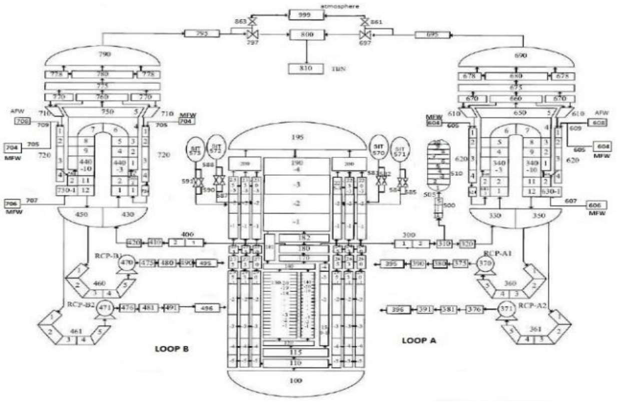

Figure 3: Nodalization diagram of APR1400 modeled for a SBO

II. OPTIMAL PROCEDURES DURING SBO

The challenge encountered in NPPs industry after the Fukushima accident is how to cope with risks caused by beyond design basis accidents (BDBA), especially SBO and loss of ultimate heat sink (LUHS). Our scenario presents the optimal procedures to mitigate SBO within the first eight hours.

TD-AFWPs start to inject feedwater into the SGs at a flow rate of 41 kg/s during the first 30 mins. In order to create an equilibrium between the heat transfer from the RCS to the SGs; the heat is removed from the SGs through the ADVs following this period. After 30 mins, The ADVs are manually opened to initiate cooldown of the secondary side; the flow rate of the feedwater decreases to 19 kg/s.

With loss of all station AC power (SBO), RCP seal cooling water will be lost. The NRC has postulated in their evaluation of SBO that, under these conditions, the seals will begin to degrade and gross seal leakage on the order of several hundred gpm may occur [3]. The RCP seals are assumed to fail at 3 mins with 120 gpm (7.55 kg/sec.) in this scenario.

Decay heat removal can be provided by the SIS, without SIPs, using the borated cooling water from the SITs. The SITs are normally pressurized to a nominal operating pressure of 610 psig (42 bar) and 48.9 ^{0}C for normal operation.

A passive fluidic device, which is installed in each of the SITs, provides two operational stages of a safety water injection into RCS, resulting in a more effective use of borated water in the SITs in the event of emergency. The fluidic device initially delivers a high flow rate of safety injection water for the certain period of time; and thereafter, the flow rate is reduced to about 30% of high flow rate [3]. RCP seal leakage causes a rapid RCS pressure decrease until the SITs injection pressure is reached. The SITs are assumed to open approximately one hour after SBO.

III. RESULTS

Figure 4 shows the relationship between the AFW flow rate and the mass flow rate through the ADVs. In this procedure, when the cooldown procedure was initiated 30 mins after SBO, the ADVs were opened to approximately 30 % of their total capacity to relieve the SG pressure, which started at 26 kg/s and then reach the maximum value of 65 kg/s. It was observed that the ADVs mass flow rate decreased as the AFW flow rate decreases.

The seal of RCPs is assumed to fail 3 mins after SBO in this scenario with a leakage rate of 7.4 kg/s of each RCP, causing a rapid RCS pressure decrease. There is a sharp fall in the seal leakage rate with the reduction in pressure difference between the RCS and the atmosphere in the containment. When the SITs start to inject borated water into the reactor vessel at the 54th min, the seal leakage slowly decreases, as shown in Figure 5.

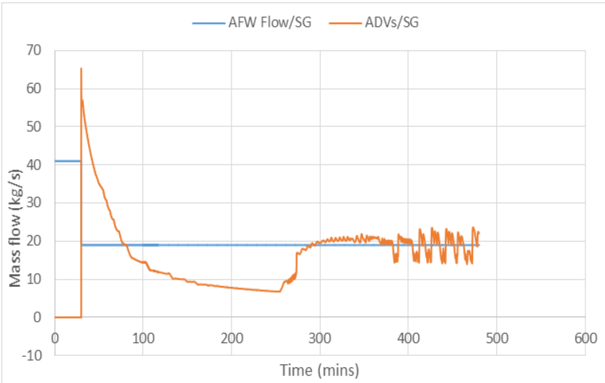

Figure 4: AFW and ADVs Flow Rates

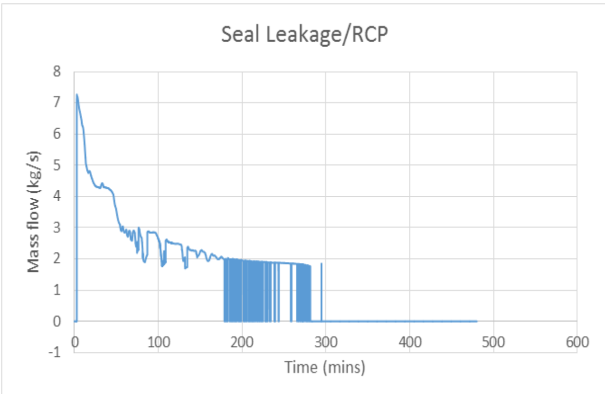

Figure 5: RCP Seal Leakage

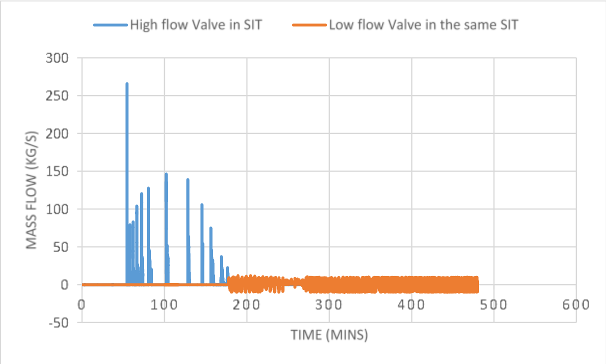

Figure 6: SIT Flow Rate

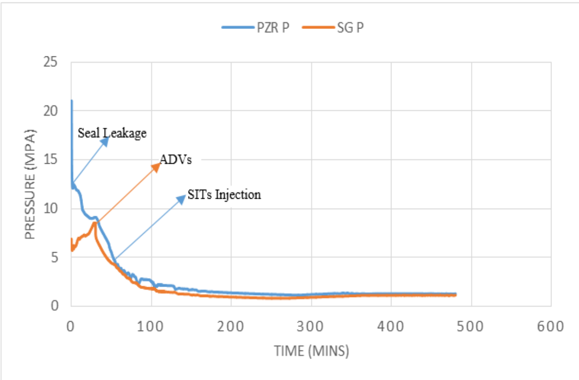

Figure 7: Pressure of Pressurizer and Steam Generator

Displayed in Figure 6, the SITs start to inject the borated water at approximately one hour, dependent on the RCS pressure. Each SIT contains a fluidic device, which has two valves for different flow rates at specified periods. The first valve starts the borated water injection from the 54th to the 177th min. and the second valve from the 177th to the 480th min. Figure 7 shows the pressure of the primary and secondary side during SBO.

IV. CONCLUSION AND DISCUSSION

From the results, the AFWS can successfully cooldown the RCS and provide at least 8 hours of additional time for the operator to restore the electric power to prevent core damage.

It is recommended to extend the life time of the batteries to be able to continue AFWS operation for coping with SBO. Station blackout without operator action (cooldown procedure) leads to core damage at 2.0 hours and reactor pressure vessel failure at 3.7 hours in APR1400 [4].

TD-AFWPs of APR1400 are necessary to mitigate SBO. However, If 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 SGs boil dry at about 40 mins. Primary pressure then rapidly rises and the POSRVs are still opened. The core will uncover; and thus, core damage will occur unless power is restored and auxiliary feedwater flow is established.

There are many alternatives to mitigate an extended SBO such as fire trucks which inject the cooling water directly into the SGs and the reactor vessel. Alternatives like this require preparation time to stage since they contain portable devices.

Another alternative, when AFWS fails, would be the passive systems. The use of passive systems can eliminate the need for electric power supplies.

CONFLICT OF INTERESTS

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

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