Evaluation of the Passive Auxiliary Feedwater System to Mitigate the the Loss of Ultimate Heat Sink Accident for APR1000

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1. Introduction

Design Extension Condition (DEC) such multiple failure accident requests the mitigation strategies to Nuclear Power Plant (NPP)[1]. Loss Of Ultimate Heat Sink (LOUHS) is one of multiple failure accident keeping not to grow up severe accident by the mitigation capability during transient. Advanced Power Reactor 1000 (APR1000) has developed to comply with the DEC requirements Western European Nuclear Regulators Association (WENRA) suggested by the International Atomic Energy Agency (IAEA). APR1000 is a two-loop pressurized water reactor which produces the electrical power about 1,000 MWe and has some unique enchanced safety features such as Passive Auxiliary Feedwater System (PAFS). The traditional valves for depressurization the Reactor Coolant System (RCS) such as Atmospheric Discharge Valves (ADVs) are also installed from commercial nuclear power plant.

The LOUHS during normal operation results in the loss of Essential Service Water System (ESWS) and Circulation Water System (CWS). Even though the loss of function for equipment using ESWS or CWS directly or indirectly takes time in real situation, it is assumed that all of systems are lost at the initiation of LOUHS. Operator could mitigate the accident not to develop to severe accident using PAFS and ADVs. To evaluate the PAFS performance, accident analysis of LOUHS is compared with the case using Auxiliary Feedwater System (AFWS). The time that reached Shutdown Cooling System (SCS) entry condition and fuel cladding temperature are referred to demonstrate the mitigation performance by PAFS or AFWS.

2. Analysis Methodology

2.1 Plant Modeling and Initial Conditions

APR1000 had developed based on the OPR1000 and APR1400 with the safety key features such as Direct Vessel Injection (DVI) with Emergency Core cooling Barrel Duct (ECBD), Safety Depressurization and Vent System (SDVS) and PAFS. The radiation exposure levels below the regulatory limits are obtained by these safety functions for mitigating and terminating DEC accidents. The node diagram of RCS main components including PAFS is shown in Figure 1 for best estimated safety analysis using SPACE code[2].

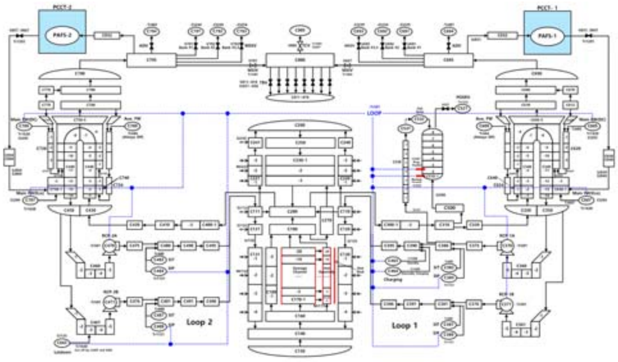

Figure 1. APR1000 Node Diagram

Best estimated safety analysis is performed with control systems model including Pressurizer Pressure Control System (PPCS), Pressurizer Level Control System (PLCS), Feedwater Control Control System (FWCS) and Steam Bypass Control System (SBCS). To simulate thermal hydraulic phenomena with response of various control systems during LOUHS, the SPACE code is used to predict reactor kinetics and thermal hydraulic phenomena. The transient starts at the realistic initial conditions as shown in Table I.

Table I. Initial Conditions

Parameter	Design Value	Analysis Value
Core Power, MWt	2,815.0	2,815.0
PZR Pressure, MPa	15.5	15.5
RCS Flow Rate, kg/s	15,309	15,304
Core Inlet Temperature, K	600.4	599.9
Secondary Pressure, MPa	7.5	7.5
Secondary Steam Flow Rate, kg/s	803	798
PZR Level, %	52.6	52.2
Steam Generator Level, % WR	79.0	79.0

2.2 Assumptions

The LOUHS during normal operation results in the loss of ESWS, therefore, the systems and equipments using essential service water will be affected in consecutive order with time delay. For conservative analysis the loss of the CWS is also assumed that brings into the loss of condenser vacuum and feedwater pumps trip, sequentially. As following the feedwater pumps trip, turbine would stop slowly, however, it is assumed that the turbine stops instantly to simulate more conservative transient. The loss of the Steam Bypass

Control System (SBCS) is also assumed at the beginning.

Table II. Systems Available for LOUHS

Systems	Assumptions
Pressurizer Level Control System	Credit
Pressurizer Pressure Control System	Credit
Steam Bypass Cutback System	Not Credit
Feedwater Control System	Credit
Atmospheric Dump Valves	Available
Reactor Coolant Gas Vent System	Available

2.3 Compare PAFS with AFWS

AFWS is well verified to cool down steam generator (SG) and operated by the electric energy or steam flow after reactor trip. The PAFS is a passive means during LOUHS where the main feedwater is unavailable. The decay heat is removed passively through the Passive Condensation Heat Exchangers (PCHXs). As an inevitable means, the operator action should be performed with enough margin to perform mitigation action by the emergency operation guideline for LOUHS. It would be concluded that faster mitigation case has larger operation preparation time to cope with the LOUHS.

3. Analysis Results

The sequence of event including time and description is shown in Table III during LOUHS with PAFS. At the beginning of the LOUHS, the loss of cooling function of ESWS induces the Loss Of Condensate Vacuum (LOCV). Turbine is stopped and the feedwater pumps are also stopped. At the 41 seconds, the reactor trip occurs by the Low Steam Generator Level (LSGL) signal.

Table III. Sequences of Event

Sequences	Time (second)
LOUHS Occurs Loss of ESWS, CWS LOCV (Turbine Trip, FWP Trip) Letdown Isolation	0.0
Reactor Trip by LSGL	41
MSSV Open	48
PAFS Actuation	74
Operator Action - RCP Trip - CP Trip - ACP Actuation - RCGVS Open	1,800
SCS Temperature Entry Condition Reached (350 °F)	9,620
SCS Pressure Entry Condition Reached (410 psia)	32,180

The liquid mass of SG is decreased as shown in Figure 1 due to remove the decay heat. After reactor trip occurs, the SG level decreases rapidly and reached to the low steam generator level signal for actuating the PAFS and AFWS of wide range 24.5% as shown in Figure 2.

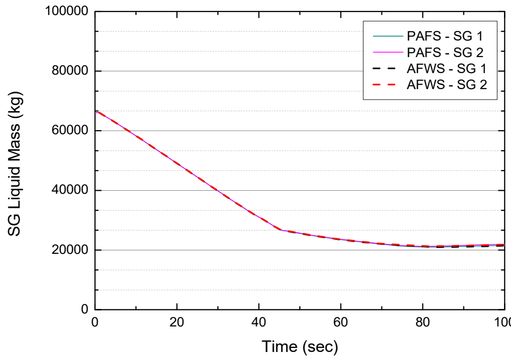

Figure 1. SG Liquid Mass

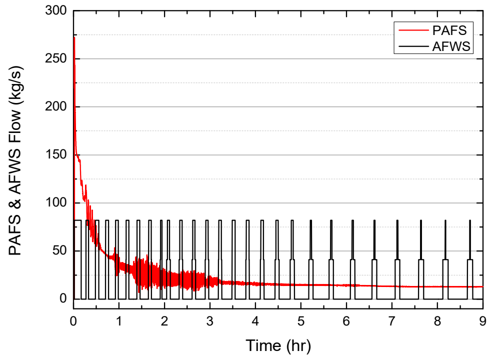

Figure 2. PAFS Flow

In the beginning of the transient with PAFS, the water in the PAFS is added into the SG. The decreasing of the SG liquid is detected, however, steam-liquid mixture is circulated in the PAFS. SG pressure is increased by the loss of feedwater and the secondary coolant is discharged through the Main Steam Safety Valve (MSSV) as shown in Figure 3.

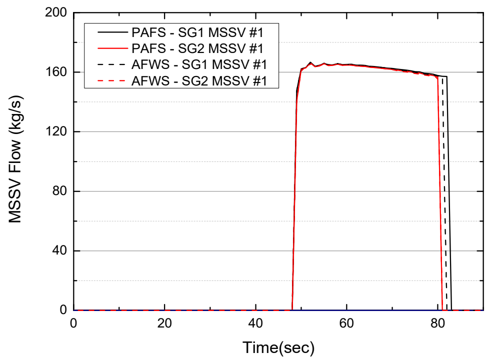

Figure 3. MSSV Flow

At the beginning of the LOUHS, the RCS is depressurized through secondary systems as shown in Figure 4. For the case with PAFS, the RCS pressure increases from 700 seconds when the safety injection pump is actuated by the low pressurizer pressure signal to 1,800 seconds when the operator action is assumed. For the case with AFWS, RCS pressure is not decreased by the secondary system even though discharging coolant through Pilot Operated Safety and Relief Valve (POSRV), and the RCS depressurization is delayed until operator action is performed. Therefore, the time that RCS pressure is reached to the SCS entry condition is slower than about 5 hours of the case with PAFS.

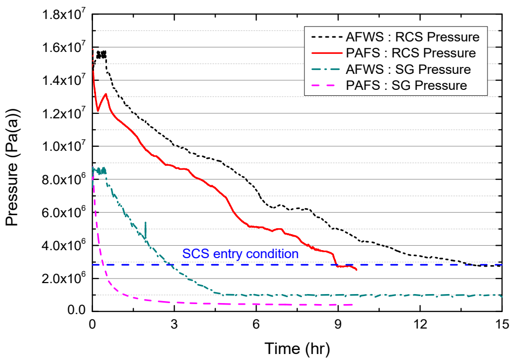

Figure 4. Pressure

At 1,800 second, operator isolates the safety injection and trips RCP and Charging Pump (CP). Because the minimum flow of the heat exchanger of the CP is lost the function, the operator also has to actuate the Auxiliary Charging Pump (ACP). The operator actuates the Reactor Coolant Gas Vent System (RCGVS) for RCS natural circulation. The hot leg temperature rises for a short time due to the decreased charging flow but it is cool down continuously and reached the SCS entry temperature as shown in Figure 5. For the case with AFWS, RCS temperature begins to decrease, however, it is reached to the SCS entry temperature condition very slowly.

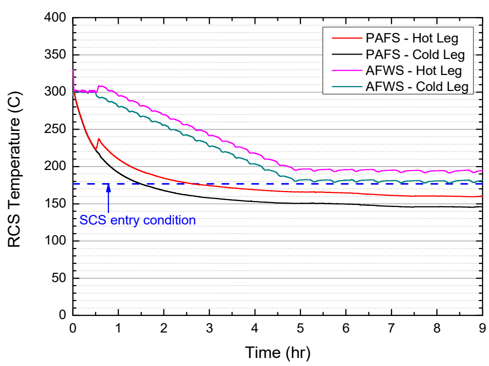

Figure 5. RCS Temperature

For the case with AFWS, operator should open the ADV to depressurize RCS as shown in Figure 6. Decreasing the RCS coolant temperature by the PAFS, the fuel is cooled well and the fuel integrity remains. After the RCP trip by operator, RCS flow is decreased then the temperature difference from the hot leg and cold leg increases as shown in Figure 5, therefore, this affects the fuel cladding temperature as shown in Figure 7.

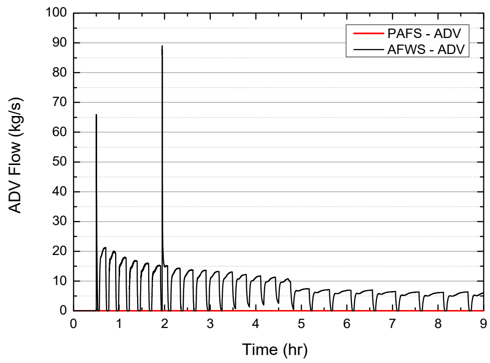

Figure 6. ADV Flow

For the case with AFWS, fuel cladding temperature is not also harmful, however, it has more safety margin to mitigate LOUHS that the case with PAFS in a view of operator action.

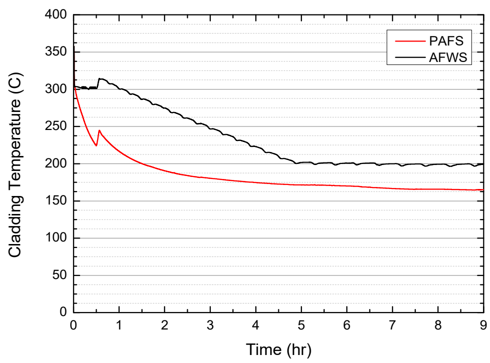

Figure 7. Fuel Cladding Temperature

4. Conclusions

The mitigation time of the case with PAFS is shorter than the time of the case with AFWS. Moreover, the operator action is not required in the case with PAFS. Therefore, it is concluded that the PAFS is more effective to stabilize RCS during LOUHS.

REFERENCES

[1] KINS/RG-N16.01, Rev.0, Regulatory Guideline 16.1, “Assessment of accidents due to multiple failures”, 2016.
[2] TR-KHNP-0032, “원전 설계용 SPACE 코드 특정기술주제보고서”, 2017.