Conceptual Design of Additional Injection Tank for Heat Load Reduction on Reactor Vessel Lower Head during Severe Accident

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1. Introduction

The in-vessel retention through external reactor vessel cooling (IVR-ERVC) is adopted for the APR 1400 as a severe accident management strategy to remove decay heat from molten corium. The core-melt progression process is divided into two phases, early-phase and late-phase. During early-phase core-melt progression, the molten corium set to first relocation in the lower head. From the first relocation of molten corium to reactor vessel failure is called late-phase core-melt progression.

Additional coolant injection would be effective to remove core decay heat without any safety injection pump operations, particularly during the late-phase core-melt progression to cool relocated corium.

Generally it's regarded as the success of IVR-ERVC when the heat flux of the RPV wall is lower than the critical heat flux on any location of the vessel external surface. To improve feasibility of IVR-ERVC, thermal margin improvement can be considered by either enhancing coolability or reducing the heat load on the external wall of reactor vessel lower head.

In this paper, the additional injection tank designs were suggested with following core-melt progression analysis in order to reduce the heat load and optimize the injection setpoints for APR 1400.

The core-melt progression analysis was performed using modular accident analysis program (MAAP4) code under the 4 setpoint cases of the additional injection tank for several accident scenarios.

2. Additional injection tank designs

Considering the driving force of passive injection system, pressure difference and gravity, accumulator design and the gravity driven injection (GIT) design, both have direct vessel injection(DVI) line and same capacity(51.2 ton) with one safety injection tank(SIT), can be applied, shown in Fig. 1. Accumulator design, utilizing the injection methodology and structure of the SIT, uses the check valve that opens when the pressure in the reactor vessel is lower than that in the accumulator design. GIT design, using elevation difference, has two valves, one connected with the top of the tank and another connected with the bottom, that being open simultaneously by a signal. Through the bottom valve, the coolant in the tank is injected into the reactor vessel. According to the IAEA-TECDOC report [1], the GIT design is a passive safety system.

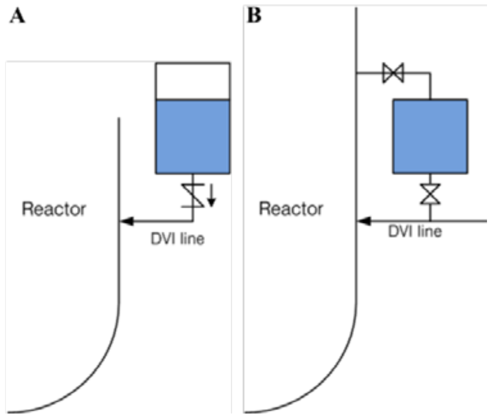

Fig. 1. Suggested tank designs
(A: Accumulator type, B: Gravity driven tank type)

The condition of core exit temperature (CET) over 1200˚F is regarded as core damage with general RV pressure ranges from 3 to 6 bar. Considering the conditions of the pressure and the CET during severe accident, the four setpoints were applied as follows.

Setpoint (1): Maximum CET=1200˚F
Setpoint (2): Primary system pressure=4 bar
Setpoint (3): Primary system pressure=5 bar
Setpoint (4): Primary system pressure=6 bar

3. Core-melt progression analysis

To investigate the feasibility of the additional injection tank and optimize the setpoints for the APR 1400, the core-melt progression analysis was conducted by using MAAP4 code.

3.1 Accident scenarios

To perform the core-melt progression analysis, the accident scenarios of high core damage frequency were considered and the loss of feed water (LOFW), small break loss of coolant accident (SLOCA), medium break loss of coolant accident (MLOCA) and large break loss of coolant accident (LLOCA) cases were determined.

3.2. MAAP4 calculation results

For accident scenarios of LOFW17, SLOCA23, MLOCA4 and LLOCA4, the core-melt progression analysis was conducted under the four setpoint cases of the additional injection tank. And the MAAP4 calculation results were compared with the results of APR1400 without the additional injection tank. Assuming conditions with no gap cooling, no ERVC, and the two-layer formation of oxide and metal layer, the additional injection tank was simulated by the high pressure safety injection pump (HPSIP).

For each test cases, the timing analysis results of the main events such as the core uncovery, the first relocation and the vessel failure were shown in Table Ⅱ.

Case (0): APR1400 type case without the additional injection tank

Case (1): APR1400 type case with the additional injection tank of the setpoint (1)

Case (2): APR1400 type case with the additional injection tank of the setpoint (2)

Case (3): APR1400 type case with the additional injection tank of the setpoint (3)

Case (4): APR1400 type case with the additional injection tank of the setpoint (4)

Table I: Accident case for core-melt progression analysis

Sequence	Sequence description
LOFW17	(LOFW)(reactor trip)(failure to deliver feed water) (safety dep. for bleed OK) (safety injection for feed fails)
SLOCA23	(Small LOCA)(reactor trip OK)(safety injection fails)(aggressive cooldown fails)
MLOCA4	(Medium LOCA)(safety injection fails)
LLOCA4	(Large LOCA)(SIT OK)(Safety Injection fails)

Table Ⅱ: Main event timing under accident scenarios

(unit: second)

	Case	Core uncovery	First relocation	Vessel failure
LOFW17	Case (0)	3,536	18,443	28,624
	Case (1)	3,536	19,712	26,967
	Case (2)	3,536	21,975	31,187
	Case (3)	3,536	22,533	31,112
	Case (4)	3,536	22,736	30,985
SLOCA23	Case (0)	1,117	19,582	26,267
	Case (1)	1,117	18,548	25,933
	Case (2)	1,117	20,587	29,276
	Case (3)	1,117	22,859	32,590
	Case (4)	1,117	22,892	32,247
MLOCA4	Case (0)	1,136	20,286	26,133
	Case (1)	1,136	19,104	27,344
	Case (2)	1,136	20,518	32,099
	Case (3)	1,136	22,156	32,129
	Case (4)	1,136	22,292	31,677
LLOCA4	Case (0)	4,510	8,293	15,541
	Case (1)	4,510	10,802	18,010
	Case (2)	4,510	10,998	18,539
	Case (3)	4,510	10,629	18,217
	Case (4)	5,601	9,581	17,413

Table Ⅲ: Decay heat of relocated corium

(unit: MW)

Case	LOFW17	SLOCA23	MLOCA4	LLOCA4
Case 0	27.2	23.5	23.6	22.3
Case 1	26.0	19.4	23.6	23.1
Case 2	26.0	22.5	19.3	23.2
Case 3	26.1	22.6	22.5	22.7
Case 4	26.4	22.6	22.4	22.4

For LOFW17 scenario, the coolant of the additional injection tank is injected before the first relocation and has an effect of delay of the first relocation under all setpoint cases. And for all setpoint cases except for the case (1), it takes longer time than for the case (0) until the vessel failure.

For SLOCA23 and MLOCA4 scenario, the coolant of the additional injection tank is also injected before the first relocation. And for all setpoint cases except for the case (1), it takes longer time until the vessel failure. For LLOCA4 scenario, the coolant of the additional injection tank has an effect of delay of the first relocation and the vessel failure under all setpoint cases. However, for the case (4), the coolant is injected before the core uncover event and has a role of the engineering safety feature (ESF) system.

Table Ⅲ shows the decay heat of the relocated corium. It was confirmed that the heat load is reduced by the additional injection tank due to the timing delay of the vessel failure.

3. Conclusions

In this study, to reduce the heat load, the method of the coolant injection to the reactor vessel was utilized and the additional injection tank designs such as the accumulator and GIT design were suggested.

The core-melt progression analysis was conducted by using MAAP4 code, to investigate the feasibility of the additional injection tank and optimize the setpoints for the APR 1400. The analysis was for the four setpoint cases and four accident scenarios.

For most cases, the coolant of the additional injection tank is injected before the first relocation and has an effect of delay of the first relocation and the vessel failure timing. And it was regarded that the heat load is reduced by the additional injection tank because the timing delay of the vessel failure. For further works, the setpoint design in late-phase core melt progression process and the direct cooling process of the relocated corium in lower head should be considered.

REFERENCES

[1] J. H. Choi, "Passive Safety Systems and Natural Circulation in Water Cooled Nuclear Power Plants", IAEA-TECDOC-1624, 2009.