

Preliminary Analysis of an MMPS Charging-Line Break in the i-STEP Integral Effect Test Facility

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1. Introduction

An innovative small modular reactor (i-SMR) is being developed in Korea with fully passive safety systems for accident mitigation. The major passive safety systems (PSSs) include the passive auxiliary feedwater system (PAFS), passive containment cooling system (PCCS), and passive emergency core cooling system (PECCS). During a loss-of-coolant accident (LOCA), these systems are designed to remove decay heat from the reactor coolant system (RCS), depressurize the reactor vessel (RV) and containment vessel (CV), and maintain sufficient coolant inventory without relying on active safety injection systems.

The i-SMR integral effect Test Evaluation Platform (i-STEP) is being developed at the Korea Atomic Energy Research Institute (KAERI) for integral-effect validation of the thermal-hydraulic behavior of the i-SMR [1,2]. The facility is designed based on the three-level scaling methodology, with the major geometric and thermal-hydraulic characteristics of the prototype preserved as closely as practicable. In particular, the RV, CV, PAFS, PCCS, and PECCS are incorporated to reproduce the

interactions among the RCS, CV, and PSSs during transient and accident conditions.

A break of the charging line of the Modular Makeup and Purification System (MMPS) is one of the LOCA scenarios considered for the i-SMR, as shown in Fig.1. An important characteristic of this scenario is the low elevation of the charging-line connection on the RV. In i-STEP, the MMPS charging-line connection is located at approximately the same elevation as the emergency recirculation valve (ERV) of the PECCS. Therefore, the hydraulic role of the MMPS charging line may change significantly during the accident. At the beginning of the transient, the line provides a discharge path from the high-pressure RCS to the CV. After depressurization and the establishment of PECCS recirculation, however, the same line may provide an additional return path from the CV to the RV together with the ERVs.

In this study, a preliminary SPACE analysis was performed for an MMPS charging-line break in i-STEP. Particular attention was given to the transition of the MMPS charging line from an initial break discharge path to a potential recirculation path following PECCS actuation.

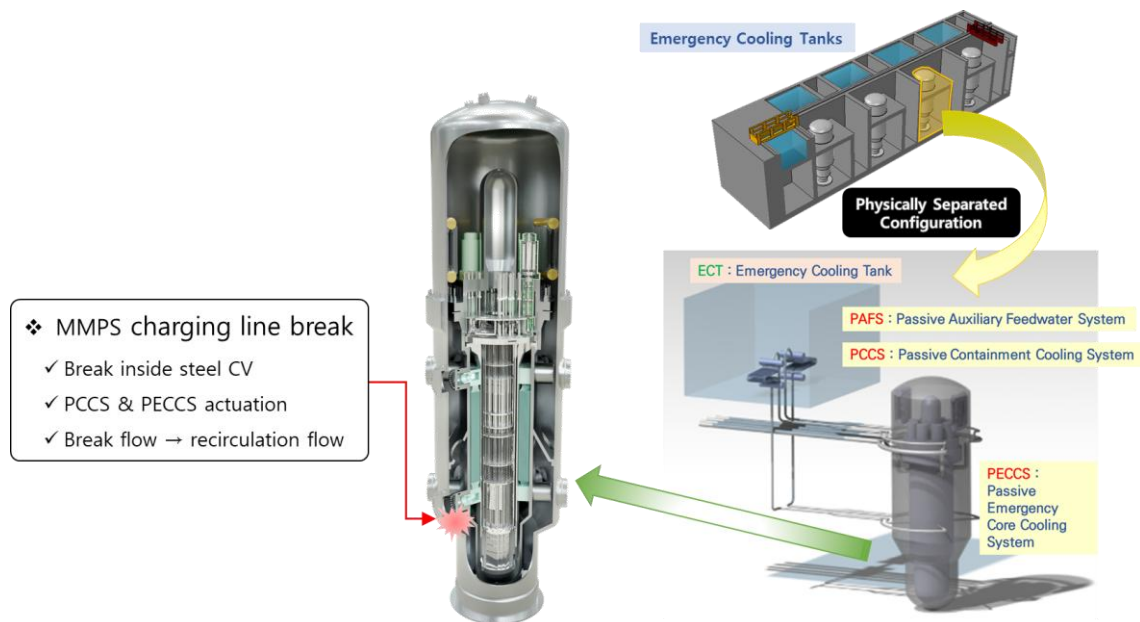


Fig. 1. Schematic of the i-SMR passive safety systems and MMPS charging-line break.

2. i-STEP Configuration for MMPS Charging-Line Break

Figure 2 shows a schematic of i-STEP and the major passive safety systems relevant to the present accident. The PECCS establishes hydraulic connections between the RV and CV through emergency depressurization valves (EDVs) and emergency recirculation valves (ERVs). During the initial depressurization phase, the EDVs provide additional discharge paths from the RV to the CV. At a later stage of the accident, when the CV water level rises sufficiently and the RV-to-CV pressure difference decreases, the ERVs provide gravity-driven recirculation flow from the CV to the lower part of the RV.

The MMPS charging line and the ERVs are connected to the lower region of the RV at the same elevation in i-STEP. Although the two connections appear to be at different elevations in Fig. 2 because of overlapping piping and components, their actual connection elevations are identical. Therefore, after the CV water level rises above the connection elevation and the RV-to-CV pressure difference becomes sufficiently small, the MMPS charging line is expected to provide an additional recirculation path similar to the ERVs.

The PCCS removes heat from the CV by condensing steam on the outer surfaces of the PCCS heat exchanger tubes. The condensate accumulates in the CV and provides coolant inventory for subsequent recirculation to the RV. The PAFS simultaneously removes decay heat through the secondary system after reactor trip.

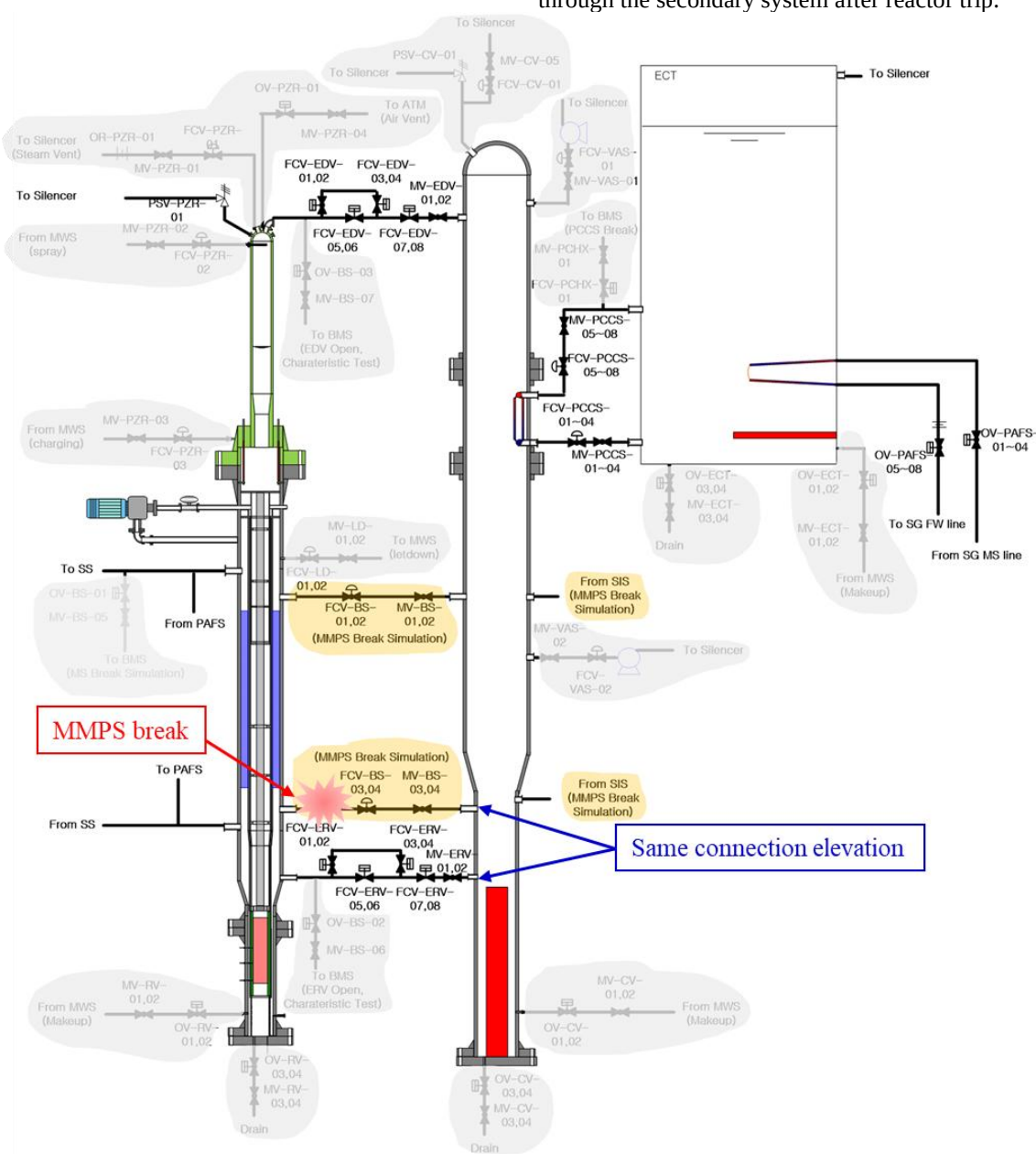


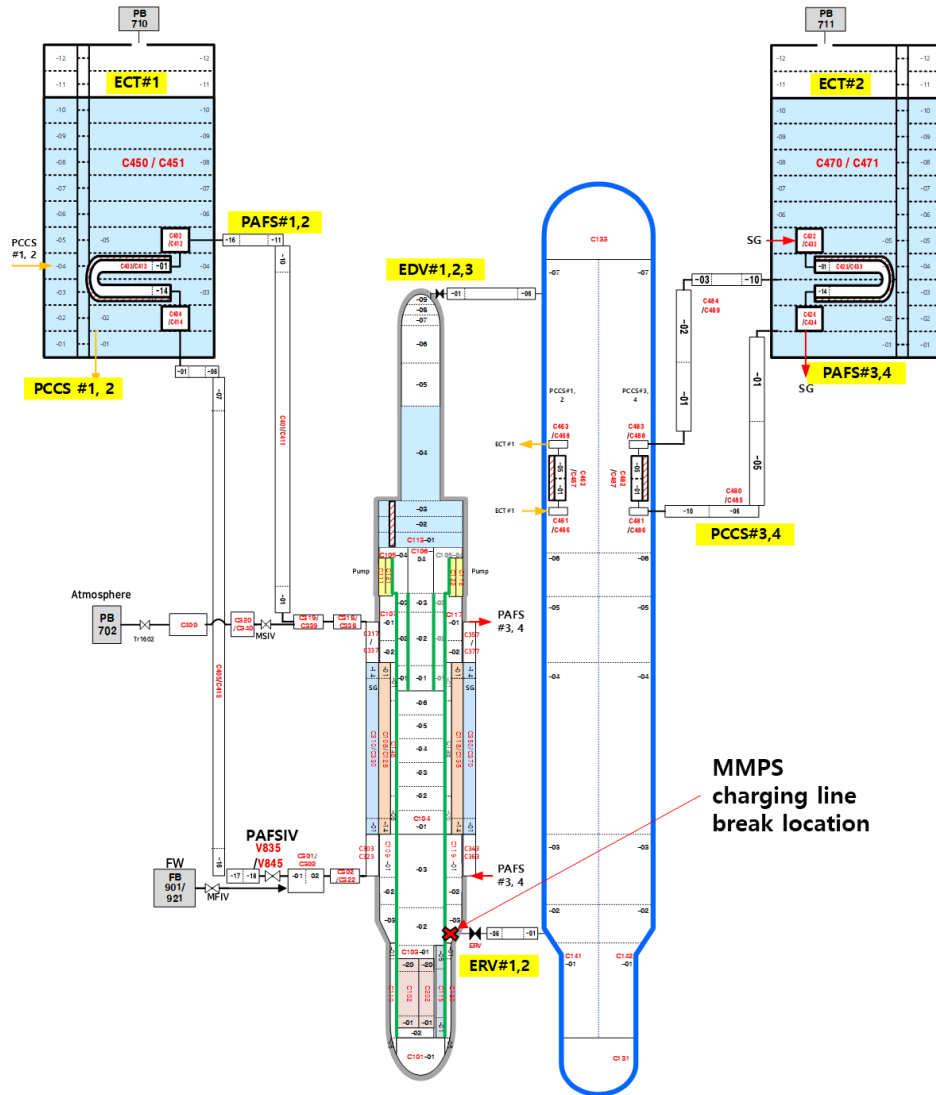
Fig. 2. Configuration of i-STEP for the MMPS charging-line break test.

3. Preliminary SPACE Analysis

3.1 Analysis model and transient sequence

A SPACE [3] input model of i-STEP was developed based on the facility design as shown in Fig. 3. The model includes the RV and core, pressurizer (PZR), steam generator (SG), CV, PAFS, PCCS, and PECCS. The MMPS charging-line break was represented as a hydraulic connection between the lower RV region and the CV.

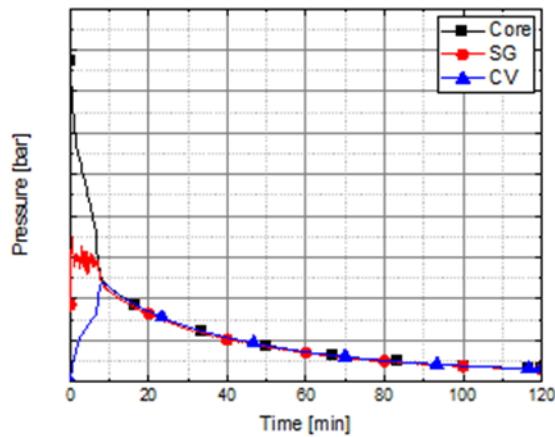
The transient was initiated by opening the MMPS charging-line break at the initial steady-state condition. Coolant discharge through the break caused rapid RCS depressurization and CV pressurization. When the CV high-pressure setpoint was reached, reactor trip and safety-system actuation signals were generated. The PAFS began removing decay heat through the secondary system, while the PECCS was subsequently actuated as the RV water level and RV-to-CV pressure difference reached the prescribed conditions.



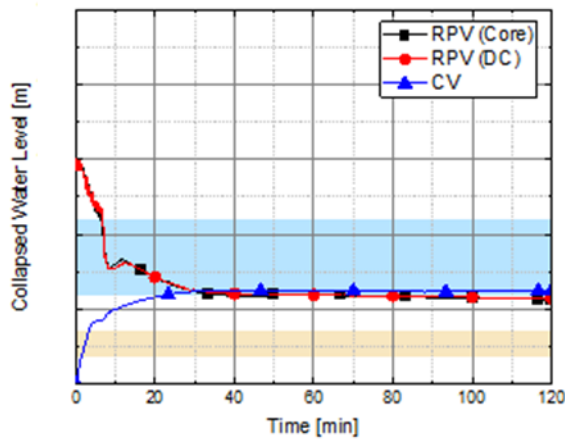
3.2 System pressure and coolant inventory behavior

Figure 4 shows the calculated RV, SG, and CV pressures together with the collapsed water levels in the RV and CV. Following the break, the RV pressure decreased rapidly due to coolant discharge through the MMPS charging line. In contrast, the CV pressure increased as mass and energy were transferred from the RCS to the containment. The difference between the RV and CV pressures decreased progressively, and the pressures approached each other during the early phase of the transient. Following pressure equalization, both pressures gradually decreased as heat was removed by the PAFS and PCCS. This behavior indicates that the driving force for outward discharge through the MMPS charging line becomes substantially reduced after the initial blowdown and PECCS actuation.

The RV water level initially decreased because of inventory loss through the break. The CV water level increased rapidly as the discharged coolant accumulated in the containment. After the early depressurization period, the RV and CV water levels approached relatively stable values. The predicted CV water level remained sufficiently high relative to the elevation of the lower RV connections to provide the hydraulic condition required for recirculation.



(a) RV, SG, and CV pressures

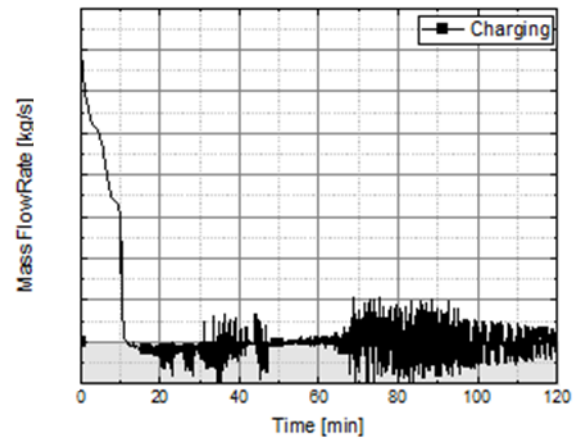


(b) RV and CV collapsed water levels

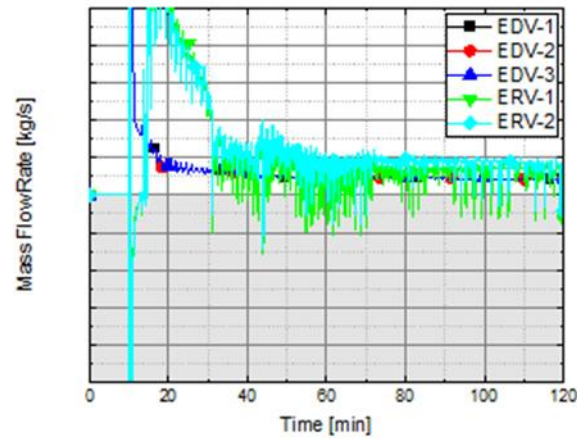
Fig. 4. Calculated pressures and water levels during the MMPS charging-line break

3.3 Transition of the MMPS charging line from break flow to recirculation flow

Figure 5 compares the calculated MMPS charging-line flow rate with the EDV and ERV flow rates over the same time period. Immediately after initiation of the accident, a large discharge flow occurs through the MMPS charging line because of the large pressure difference between the RV and CV. As the RCS depressurizes, the break flow decreases rapidly and approaches zero.



(a) MMPS charging-line flow rate



(b) EDV and ERV flow rates

Fig. 5. Calculated flow rates through (a) the MMPS charging line and (b) the PECCS EDVs and ERVs.

The PECCS is actuated approximately 10 min after the break. Following its actuation, the EDVs provide additional discharge paths from the RV to the CV, while the ERVs begin to establish recirculation flow from the CV to the RV as the RV-to-CV pressure difference decreases and the CV water inventory increases. The calculated MMPS charging-line flow also changes direction during this period.

It should be noted that the flow-direction conventions for the MMPS charging line and the ERVs are opposite in the present SPACE model. A negative MMPS charging-line flow corresponds to flow from the CV to

the RV, whereas a positive ERV flow represents the same recirculation direction. Therefore, the change in sign of the MMPS charging-line flow indicates the onset of reverse flow toward the RV.

Comparison of the two flow paths shows that the MMPS flow reversal occurs in close temporal association with the establishment of ERV recirculation following PECCS actuation. This behavior is consistent with the evolution of the system pressure and coolant inventory shown in Fig. 4. As the RV and CV pressures approach equilibrium and the CV water level increases above the lower RV connection elevation, the hydraulic driving condition for recirculation is established.

The MMPS charging line and the ERV connections are located at the same elevation in i-STEP. Consequently, once the RV-to-CV pressure difference becomes sufficiently small and the lower CV region is filled with coolant, the MMPS charging line is subjected to hydraulic conditions similar to those of the ERVs. The charging line can therefore change its hydraulic role from an initial RCS discharge path to an additional recirculation path from the CV to the RV.

These results indicate that the MMPS charging line has two distinct functions during the transient. It acts as the initiating break path during the early depressurization phase and may subsequently supplement the ERVs during the recirculation phase. The onset and magnitude of the reverse flow through the MMPS charging line, together with the ERV recirculation flow, will therefore be important parameters to be examined in the planned i-STEP experiment.

4. Conclusions

A preliminary SPACE analysis was performed for an MMPS charging-line break using the i-STEP model. The analysis focused on the hydraulic behavior of the MMPS charging line and its transition from an initial break discharge path to a potential recirculation path during the transient.

Immediately after the break, coolant was discharged from the RV to the CV through the MMPS charging line because of the large RV-to-CV pressure difference. As the RV and CV pressures approached equilibrium and the CV water inventory increased, the MMPS charging-line flow decreased and subsequently reversed toward the RV. Comparison with the PECCS flow rates showed that the MMPS flow reversal occurred in close temporal association with the establishment of ERV recirculation following PECCS actuation.

Because the MMPS charging-line and ERV connections are located at the same elevation in i-STEP, both flow paths are subjected to similar hydraulic conditions during the later phase of the transient. The preliminary results therefore indicate that the MMPS charging line has a dual hydraulic function during the accident: an RCS break path during the initial depressurization phase and a potential additional recirculation path from the CV to the RV during the long-

term cooling phase. The transition of the MMPS charging-line flow and its interaction with the ERV recirculation flow will be key thermal-hydraulic phenomena to be investigated in the planned i-STEP integral effect test.

ACKNOWLEDGMENTS

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