Review on Emergency Operating Procedures for APR1400: Feed-and-Bleed and RCS Rapid Cooldown in SLOCA

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1. Introduction

In emergency operating procedures (EOPs) of large-pressurized water reactor, feed-and-bleed (F&B) operation and reactor coolant system (RCS) rapid cooldown are considered as important strategies to prevent core damage when either secondary side cooling system fails or safety injection system fails. In here, RCS rapid cooldown strategy means that opening of main steam atmospheric dump valve (MSADV) in order to decrease RCS pressure, and accordingly, to inject safety injection tanks (SITs) or in-containment refueling water storage tank (iRWST) by shutdown cooling pumps (SCPs).

Current practice of probabilistic safety assessment (PSA) also accepts F&B and RCS rapid cooldown strategies as success criteria for specific initiating events. F&B operation strategy is applicable to not only transient events, but also loss of RCS inventory such as cold-leg small break size loss-of-coolant-accident (SLOCA) and steam-generator-tube-rupture (SGTR). RCS rapid cooldown strategy is just for the SLOCA and SGTR.

However, several researches pointed out limitations of these strategies with application of OPR-1000. Kim and co-authors [1] argued that pressurizer safety valve may not be opened even though F&B operation is necessary to prevent core damage in case of SLOCA. For RCS rapid cooldown strategy, feasibility analysis for OPR1000 was conducted [2] and they concluded there is potential for failure to initiate RCS cooldown strategy in a timely manner.

In this study, we reviewed on EOPs for APR1400 with focusing on F&B operation and RCS rapid cooldown strategies for SLOCA.

2. Materials and method

2.1. EOP for F&B and RCS Rapid Cooldown

Computerized EOPs of APR-1400 were reviewed to identify the specific steps indicating 1) F&B operation and 2) RCS rapid cooldown strategy. Fig. 1 shows existing EOP flow for CE-type nuclear power plants including OPR1000 and APR1400. After critical safety functions availability and type of design basis accidents are identified, optimal recovery procedures (ORP) for identified accident type is performed. In case of SLOCA in which F&B or RCS rapid cooling is required, (i.e., dissatisfaction of safety function status check (SFSC)), then functional recovery procedures (FRP) are performed.

2.1.1. Feed and bleed operation

In the accident in which leakage rate from RCS is a little or nothing, secondary side cooling is firstly required to remove the decay power. However, in case of secondary side cooling is not available, pilot operated safety relief valves (POSRVs) can be opened to decrease RCS pressure up to below shut-off head of safety injection pump, and to inject safety injection water.

The operator actions related to F&B operation are described in “heat removal from core and RCS” (FRP-06).

(Step 101) Check F&B operation conditions

- all S/G wide range water levels are below 2%

(Step 107) Launch F&B operation

- If the POSRV is opened by checking all of the following:
  - ✓ POSRV leak alert
  - ✓ The temperature of the corresponding POSRV discharge pipe is 140°C or higher.
- Then, manually open all POSRVs.

2.1.2. RCS rapid cooldown operation

The steps related to RCS rapid cooldown can be found in the FRP-04 (RCS inventory control). Step 13 of IC-2 in FRP-04, i.e., “RCS depressurization”, describes MSADVs opening action in order to decrease the RCS pressure while keeping not exceeding 55K/h RCS cooling rate.

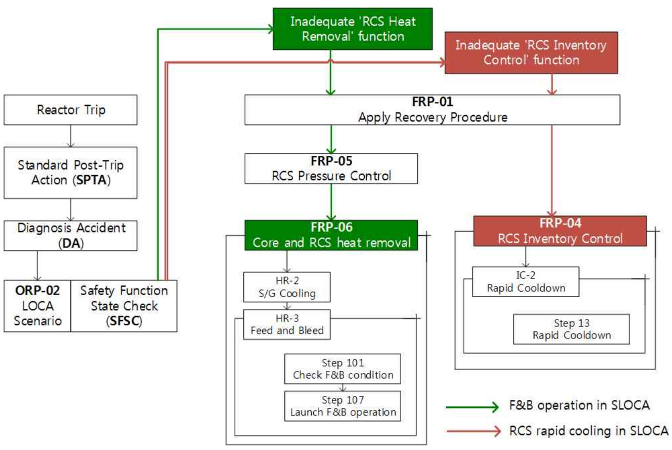

Fig. 1. Emergency operating procedures flow for F&B and RCS rapid cooling in SLOCA

2.2. Plant transient analysis for APR1400

A thermal-hydraulics analysis for F&B and RCS rapid cooling in SLOCA have been performed with the MARS (Multi-Dimensional Analysis of Reactor Safety)-KS code. With regard to the major contributor to the reactor transients, the following have been modeled.

- One safety injection pump (1 out of 4 trains) is available and safety injection actuation signal (SIAS) is generated at 124kg/cm^2 of the RCS pressure, and the delay time of the injection is 30 seconds.
- One auxiliary-feed-water pump (1 out of 4 pumps) is available and auxiliary feed actuation signal (AFAS) is generated at below 23.5% of the SG wide-range level, and the delay time of the injection is 45 seconds.
- The temperature of the injection water is 30^{o}C.
- Four RCPs are manually shut-down by operator when 1) the time from reactor trip is larger than 10 minutes and 2) the coolant's sub-cooled margin is below 15^{o}C.
- While the RCS pressure increases, the POSRVs are suddenly opened at 1.75e7 Pa, and while the RCS pressure decreases, POSRVs are gradually closed at up to 80% from 1.75e7 Pa to 1.43e7 Pa and suddenly closed at 1.43e7 Pa.
- The core damage is defined as a peak clad temperature (PCT) of 2200^{o}F (1477K).

For F&B operation, 1.0-inch-break-size SLOCA was analyzed because, in larger than 1.0 inch, safety injection pump are well operable without POSRV opening. For RCS rapid cooling operation, 2.0-inch-break-size SLOCA was analyzed because the largest break size makes the most severe condition due to large amount of leakage rate.

3. Results and Discussion

3.1. Feed and Bleed Operation

Fig.2 shows the RCS pressure and PCT transients for safety injection only available case in 0.5, 1.0, and 1.5 inch SLOCA. If POSRV opening by operators is not available, small break sizes such as 0.5 and 1.0 inch make RCS pressure gradually increase and accordingly, safety injection is not available due to safety injection pump's shut-off head. Finally, core has been uncovered and damaged.

On the other hand, for 1.5 inch or larger break size, pressure decreases enough to inject safety injection pump so decay power is properly removed. It means F&B operation is valid for 1.0 inch or smaller break size. Therefore, we focused on 1.0 inch-break-size LOCA case for reviewing F&B operation strategy of APR1400.

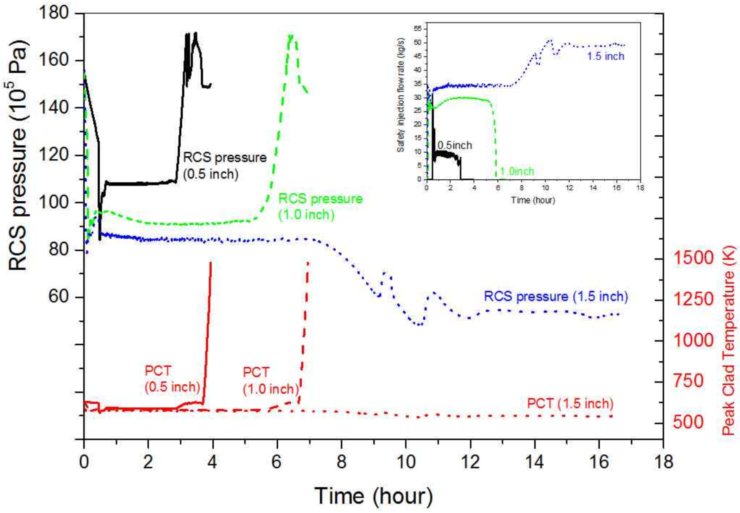

Fig. 2. RCS pressure and PCT transients for safety injection only available case in 0.5, 1.0, and 1.5 inch SLOCA

Fig.3 and Fig.4 show the plant transients for F&B operation in 1.0 inch break size LOCA. After reactor trip, safety injection is available because RCS pressure remains low enough (about 9.0e6 Pa). At the same time, SG secondary side water is gradually evaporated due to decay power. At about 2 hours, SG wide range water level reaches below 23.5%. At about 4.8 hours, SG wide range water level is finally exhausted. After that, RCS pressure gradually increases, then RCS pressure is above safety injection pump's shut-off head.

At about 6.4 hours, POSRVs are firstly opened. Based on success criteria analysis, we identified that POSRV should be manually opened within 23 minutes from POSRV initial open to prevent core damage.

Fig. 5 shows time table for plant transients and EOP flow for F&B operation in 1.0 inch SLOCA. Time difference between SG water level exhaustion and POSRV initial opening is quite long, so it is likely to fail the F&B operation in 1.0 inch break size LOCA.

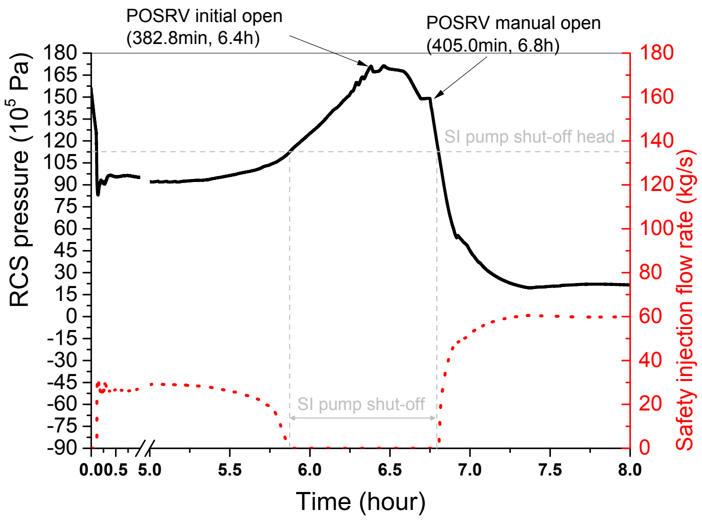

Fig. 3. RCS pressure and SI flow rate transients for F&B operation in 1.0 inch SLOCA

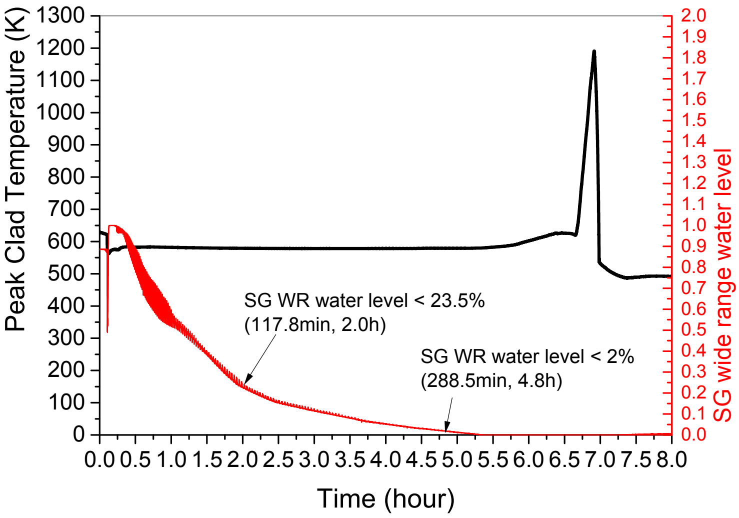

Fig. 4. PCT and SG level transients for F&B operation in 1.0 inch SLOCA

3.2. RCS Rapid Cooling Operation

As a small amount of leakage may be not severe for the reactor core cooling, SG cooling without a safety injection can sufficiently remove the entire decay power. For LOCAs of below a 1.4-inch break size of OPR1000, the reactor core was cooled by only secondary cooling without high pressure safety injection [3]. For this reason, we selected 2.0 inch break size LOCA as a bounding case.

Fig. 6 shows the RCS pressure and PCT transients for RCS rapid cooling operation in 2.0 inch LOCA. It is assumed that the rapid cooling starts 20 minutes after the start of the accident. RCS pressure stays at about 90bar because of balance between pressure increasing due to decay power and pressure decreasing due to leakage. From 20 minutes from initiation, pressure gradually decreases, however, before pressure decreases enough, core has uncovered at about 60 minutes and damaged at about 75 minutes.

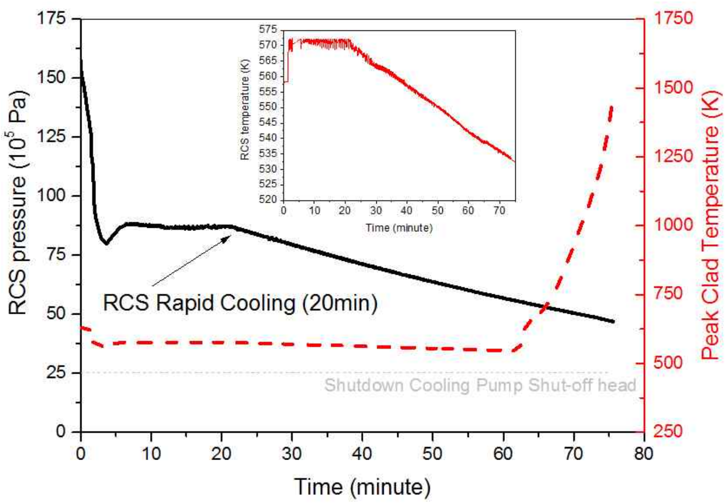

Fig. 6. RCS pressure and PCT transients for RCS rapid cooling operation in 2.0 inch SLOCA

4. Conclusion

In this research, we obtained not only the thermal-hydraulics characteristics, but also a more realistic accidents sequences for F&B and RCS cooldown in SLOCA. In the current EOPs of APR1400, F&B and RCS cooldown strategies are not valid for specific range of break size in SLOCA. As a further researches, advanced EOPs strategies to prevent core damage should be developed for entire range of SLOCA.

REFERENCES

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[3] Jaehyun Cho and et al., Quantification of LOCA core damage frequency based on thermal-hydraulics analysis, Nuclear Engineering and Design 315 (2017) 77-92.

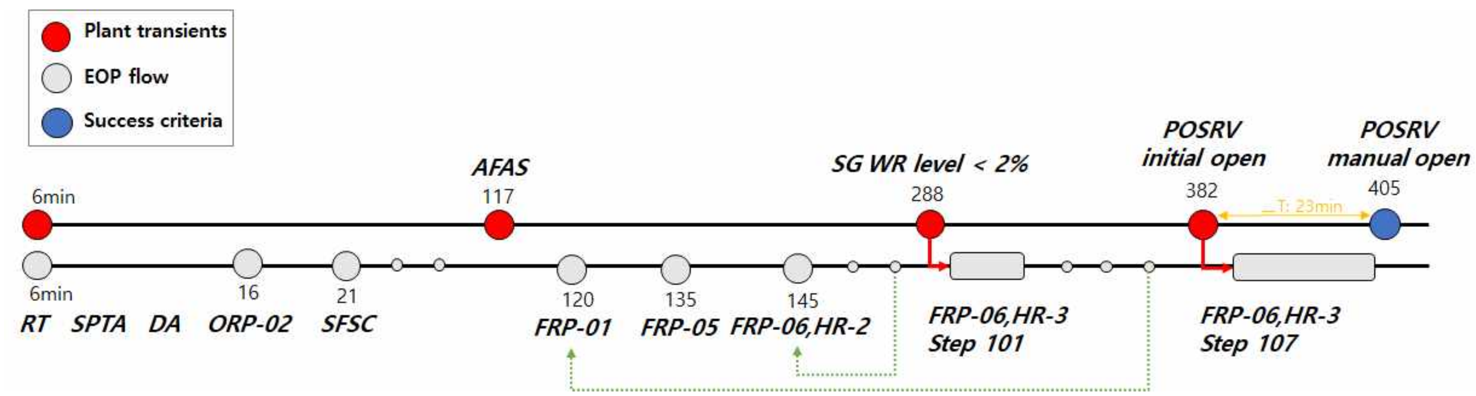

Fig. 5. Time table for plant transients and EOP flow for F&B operation in 1.0 inch SLOCA