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NUCLEAR SCIENCE AND TECHNIQUES

Nuclear Science and Techniques, Vol.17, No.4 (2006) 245–251

# Study on severe accident mitigation measures for the development of PWR SAMG

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**Abstract** In the development of the Severe Accident Management Guidelines (SAMG), it is very important to choose the main severe accident sequences and verify their mitigation measures. In this article, Loss-of-Coolant Accident (LOCA), Steam Generator Tube Rupture (SGTR), Station Blackout (SBO), and Anticipated Transients without Scram (ATWS) in PWR with 300 MWe are selected as the main severe accident sequences. The core damage progressions induced by the above-mentioned sequences are analyzed using SCDAP/RELAP5. To arrest the core damage progression and mitigate the consequences of severe accidents, the measures for the severe accident management (SAM) such as feed and bleed, and depressurizations are verified using the calculation. The results suggest that implementing feed and bleed and depressurization could be an effective way to arrest the severe accident sequences in PWR.

**Key words** SAMG, Severe accident, Mitigation measures

**CLC number** TL364$^+$.4

## 1 Introduction

The probability of severe core damage accident in PWR is very low, but once the accident occurs, it will cause core melt or even a failure of containment. To mitigate the consequences of severe accident and implement severe accident management, the Severe Accident Management Guidelines (SAMG) need to be developed.

In the development of SAMG, computational aids are necessary to analyze the accident progressions and verify the effectiveness of the mitigation measures. The first step of computational aids is to confirm the severe accident sequences in consultation with the PSA results. Referring to the PSA results, LOCA, ATWS, SGTR, and SBO hold the most part of the probability of core damage [1]. According to the influence of different initial events on CDF in USA's San Onofre NPP's IPE and Fort Calhoun's IPE, it is also clear that LOCA, ATWS, SGTR, and SBO influence CDF to a large extent [2, 3]. Therefore, the four main severe accident sequences of PWR are identifiable: LOCA sequences, SGTR sequences, SBO sequences, and ATWS sequences. Considering the development of SAMG of a Pressurized Water Reactor (PWR) with 300 MWe as an example (the assumed initial conditions are shown in Table 1), this article analyzes the progressions of the above-mentioned four accidents and verifies the effectiveness of their mitigation measures such as primary feed-bleed, secondary feed-bleed, and primary depressurization. The accident progression and the effectiveness of the mitigation measures to prevent core melt are analyzed using SCDAP/RELAP5. SCDAP/RELAP5 is the most detailed and systematic program in the world, which has the ability of simulating the thermohydraulics and the progression of core damage in severe accidents.

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Received date: 2005-11-07

## 2 Calculation model

The calculation model includes the primary loop of the plant, mainly consisting of the pressurizer(PRZ), steam generator (SG), reactor pressure vessel (RPV), reactor coolant pump (RCP), and other connecting pipes, the safety injection system consisting of high-pressure safety injection system, accumulator, and low-pressure safety injection system. The secondary side model consists of the main feedwater system (MFW), auxiliary feedwater system (AFW), main steam pipes, turbines, and so on.

**Table 1** Initial conditions

| Parameters | Values |
|---|---|
| Reactor power | 998.6577 MW |
| RCS (Reactor Coolant System) average temperature | 575.1548 K |
| Pressurizer pressure | 15.3013 MPa |
| Pressurizer water level | 5.4 m |
| RCS mass flow through loops | 3490 $kg{\cdot}s^{-1}$ |
| SG pressure | 5.737 MPa |
| SG level (narrow range) | 10.474 m |
| Turbine inlet steam flow | 542.4 $kg{\cdot}s^{-1}$ |

## 3 Analysis of LOCA sequence

### 3.1 Assumption

The base case of SBLOCA sequence assumes that the small break (25.4 mm in diameter) [4] occurs in the inlet of RPV while the safety injection system and AFW are not available.

### 3.2 Description of accident progressions

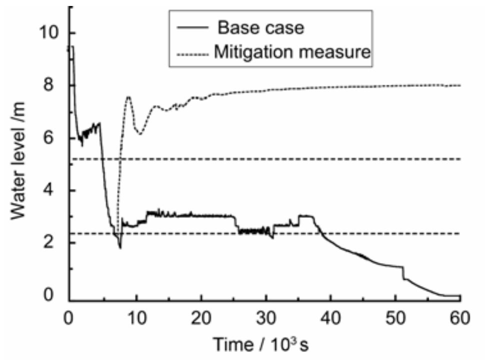
Table 2 and Fig. 1 show the accident sequence.

### 3.3 Mitigation measures

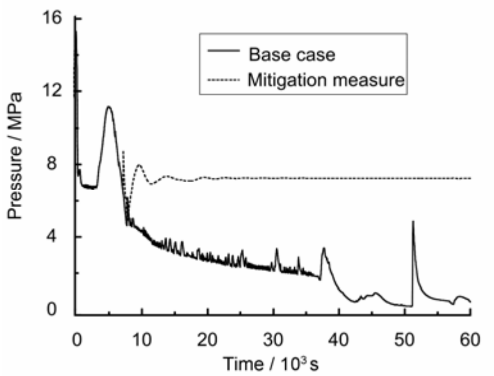
To prevent the melting of the reactor core in SBLOCA, referring to WOG SAMG, when the temperature of the core outlet exceeds 650 °C, which is set as the entry of SAMG, SAM measures should be activated to end core damage or mitigate the consequence [5]. Considering that the inventory of primary system decreases during the accident, the measure of HPIS activation is taken on the base case.

**Table 2** Analytical results for SBLOCA accident and mitigation measure sequences / s

| Progression | Base case | Mitigation measure |
|---|---|---|
| Accident begins | 0.0 | 0.0 |
| Reactor trip | 150 | 150 |
| Core begins to uncover | 4800 | 4800 |
| Accumulator activation | 7575 | / |
| Accumulator empty | 36725 | / |
| Core completely uncovered | 38775 | / |
| HPIS initiation | / | 7100 |
| Core melt starts | 41475 | / |
| Core melts down | 51175 | / |
| Lower plenum melts through | 53725 | / |
| Consequence of accident and effectiveness of mitigation measure | Core melt | Core melt is prevented |




(a) Water level in RPV.




(b) Pressure in pressurizer.

**Fig.1** Progression of postulated SBLOCA accident and mitigation measure (the two imaginary lines in Fig. 1(a) represent the top and the bottom of the core, which have the same meanings in the following figures).

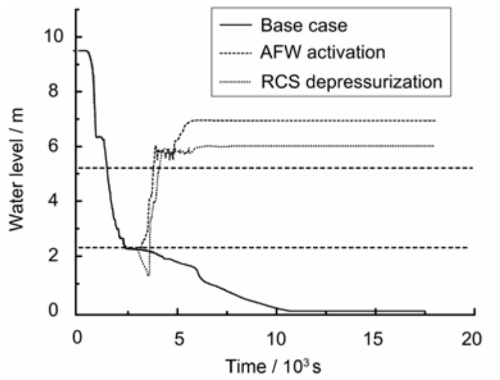
As shown in Table 2 and Fig. 1, HPIS injects coolant to the cold legs of primary loops; the injection flow reaches a balance with the break flow, and the inventory of the coolant is maintained, and the melting down of the core is mitigated.

## 4 Analysis of ATWS sequence

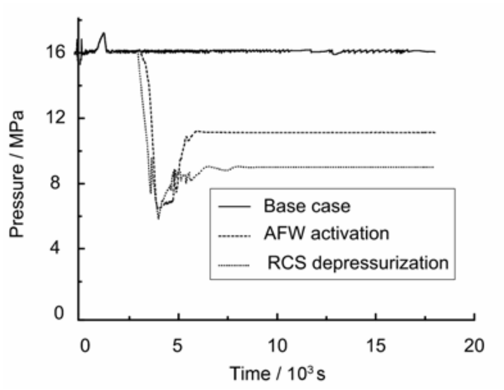
Among the most sequences of ATWS caused by mechanical sticking of the control/shutdown rods, the loss of main feedwater (LOFW), the loss of off-site power (LOOP), and uncontrolled rod cluster control assembly bank withdrawal (ICRW) may induce core damage [6] and LOFW-ATWS will be analyzed as follows. The LOFW-ATWS initial conditions are specified: initial normal full power operation at the end of core life; no scram initiation; complete loss of normal feedwater at 0 s; and unavailable AFW.

### 4.1 LOFW-ATWS accident progression

The accident sequence is shown in Fig. 2 and Table 3.




(a) Water level in RPV.




(b) Pressure in pressurizer.

**Fig.2** Progression of postulated LOFW-ATWS accident and mitigation measures.

**Table 3** Analytical results of LOFW-ATWS accident and mitigation measure sequences / s

| Sequence of accident | Base case | 1st measure | 2nd measure |
|---|---|---|---|
| Loss of feedwater | 0 | 0 | 0 |
| PRZ PORVs open | 75 | 75 | 75 |
| SG empty | 300 | 300 | 300 |
| Accumulator initiation | / | / | / |
| Core begins to uncover | 1425 | 1425 | 1425 |
| Core completely uncovered | 3425 | / | 3025 |
| AFW initiation | / | 3025 | / |
| HPIS initiation | / | 3600 | 3200 |
| Core reflooded | / | 3775 | 4075 |
| Core melt starts | 4250 | / | / |
| Hot leg creep rupture | 5200 | / | / |
| Core melt down | 16050 | / | / |
| Lower plenum melts through | 16150 | / | / |
| Consequence of accident and effectiveness of mitigation measures | Core melt | Core melt is prevented | Core melt is prevented |

### 4.2 Mitigation measures

Two mitigation measures are taken on the base case and they are described as follows.

#### 4.2.1 AFW activation

When the temperature of the core outlet exceeds 650 °C, it is assumed that AFW can be activated. As shown in Fig. 2, the residual heat in the reactor core can be removed by SG, which decreases the RCS temperature and pressure. When the RCS pressure is lower than 10.8 MPa, the HPSI can be activated, and the water level in RPV begins to rise. The core is reflooded at 3775 s. As the RCS pressure remains lower than that of the setpoint that PRZ PORVs open, the increase in the RCS inventory causes the rise in RCS pressure. When the RCS pressure reaches 10.8 MPa, the HPSI is closed, and the inventory of RCS stops increasing. Following this, the water level in RPV remains above the top of the core, thereby preventing melting of the core.

#### 4.2.2 RCS depressurization

When the temperature of the core outlet exceeds 650 °C, the PRZ PORVs are opened manually to depressurize the primary system and the pressure of RCS declines rapidly as shown in Fig. 2. The HPSI can be activated, and the water level in RPV begins to rise.

The core is reflooded at 4075s. As the HPSI flow is larger than the flow released through PRZ PORVs, the pressure and water inventory in RCS increases. When the RCS pressure reaches 9 MPa, the HPSI flow decreases to a point that is equal to the flow released through PRZ PORVs. Hence, the water level in RPV remains constant above the top of the core. The melting of the core is prevented due to the removal of the residual heat through the PRZ PORVs.

## 5 Analysis of SGTR sequence

The postulated SGTR accident in this article assumes the rupture of one U-tube near the hot-leg side of the tube sheet combined with the unavailability of the safety injection system and AFW.

### 5.1 Description of accident progressions

The accident sequence is shown in Table 4 and Figs.3 and 4.

**Table 4** Analytical results from SGTR accident and mitigation measure sequence / s

| Sequence of accident | Base case | 1st measure | 2nd measure | 3rd measure | 4th measure |
|---|---|---|---|---|---|
| Accident begins | 100 | / | / | / | / |
| Reactor trip | 340 | / | / | / | / |
| PRZ PORV opens | / | / | / | / | 14400 |
| Safety injection activation | / | 14400 | 14400 | / | / |
| AFW initiation | / | 14400 | / | 14400 | / |
| Ruptured SG overfill | / | / | / | / | / |
| Accumulator initiation | / | / | / | / | 14600 |
| Core reflooded | / | 15000 | 17200 | / | 15040 |
| Core uncover | 10930 | / | / | 10990 | 10940 |
| Core melt begins | 13360 | / | / | - | - |
| Consequence of accident and effectiveness of measure | Core melt at high pressure | Core melt isprevented | Core melt is prevented | Core melt at low pressure | Core melt at low pressure |

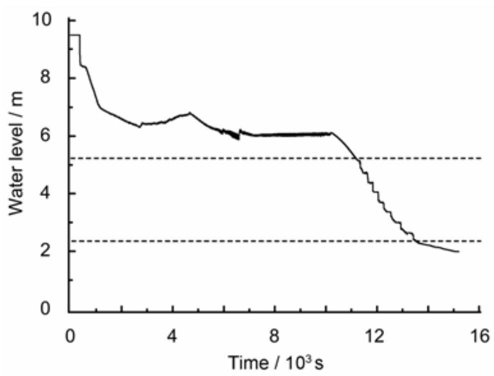



**Fig.3** Water level in RPV.

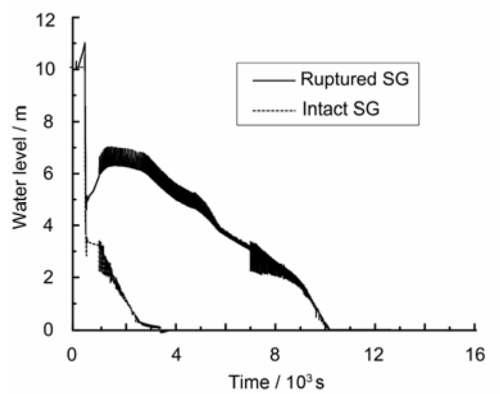



**Fig.4** Water level in SG.

### 5.2 Mitigation measures

Referring to the results of USA San Onofre NPP's IPE (Individual Plant Examination) and the previous study on SGTR accident and treatment [7, 8], the following four measures are taken to mitigate the accident.

**5.2.1** First measure: isolating the ruptured SG, initiating HPIS and AFW

After the mitigation measure is taken, the RCS inventory is replenished, the reactor core is cooled, and the highest surface temperature of fuel rods decreases to 545 K at 15000 s, and then continues to decrease at a slow pace. The coolant refloods the fuel bundles at 15000 s (Fig. 5). The initiation of AFW strengthens the cooling ability of the secondary side and raises the water level of SG (Fig. 6). Hence, the intact SG and the ruptured SG overfill soon. This measure cools the core and arrests the melting of the core effectively. However, since the primary coolant is released into the environment, the environment is polluted.

#### 5.2.2 Second measure: isolating the ruptured SG and activating HPIS

The RCS inventory increases because of the operation of HPIS, the reactor core is reflooded at 17200 s (Fig. 7) and maintains integrity. This measure can arrest the core damage progression effectively, but without AFW, the residual heat of the reactor core mainly releases to SG through the breach, and then the steam is released to the outside through the PORVs of the steam line.

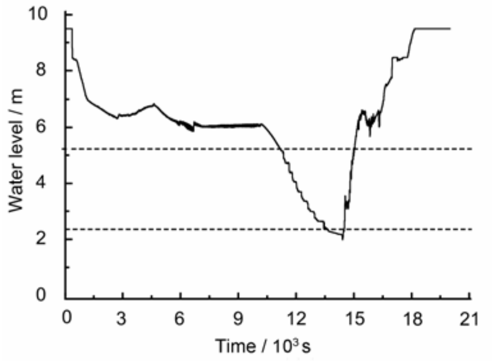



**Fig.5** Water level in RPV.

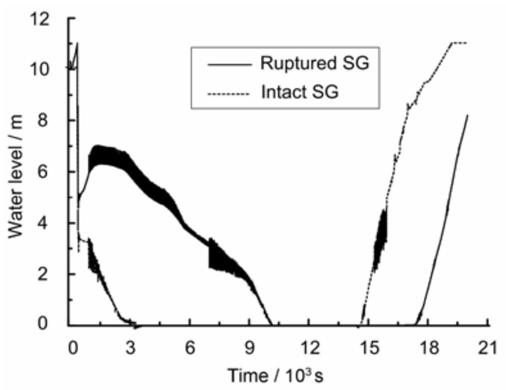



**Fig.6** Water level in SG.

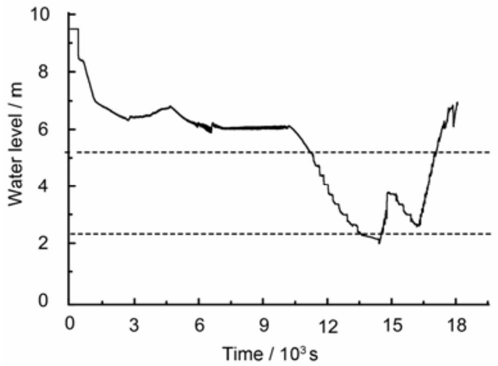



**Fig.7** Water level in RPV.

#### 5.2.3 Third measure: isolating the ruptured SG and initiating AFW

Without the replenishment of safety injection flow, RCS inventory cannot be replenished and the water level in RPV decreases gradually. The primary coolant water cannot recover the core (Fig. 8), the highest surface temperature of fuel rods continues to increase up to the limiting value, and melting of the core is inevitable. This measure cannot arrest the core damage progression effectively, and the core melts at low pressure, but it provides a secondary sink and minimizes the consequence of the accident.

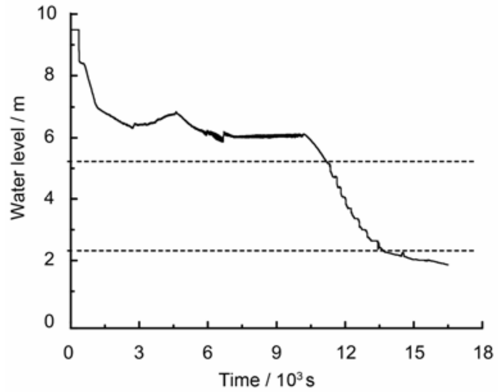



**Fig.8** Water level in RPV.

#### 5.2.4 Fourth measure: opening PRZ PORV

This measure deals with the manual opening of PRZ PORVs to depressurize the primary system. Even if the safety injection system and AFW cannot initiate, the primary pressure still decreases (Fig. 9), and the progression of the melting of the core under high pressure is changed into that under low pressure. Since the water level of the ruptured SG remains low (Fig. 10), neither overfilling nor the safety valve opening will occurs, which prevents the release of radioactivity. Although this measure cannot avoid the reactor core melt, it can minimize the consequence of the accident.

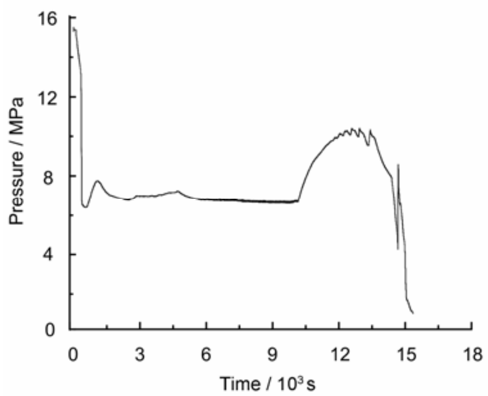



**Fig.9** Pressure in pressurizer.

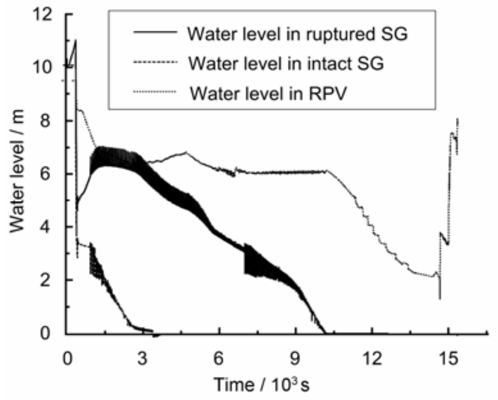


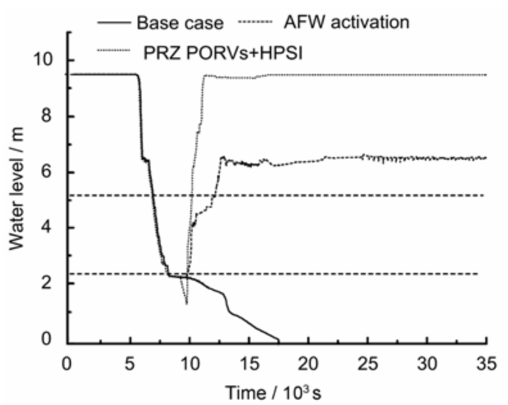

**Fig.10** Water level in RPV and SG.

## 6 Analysis of SBO sequence

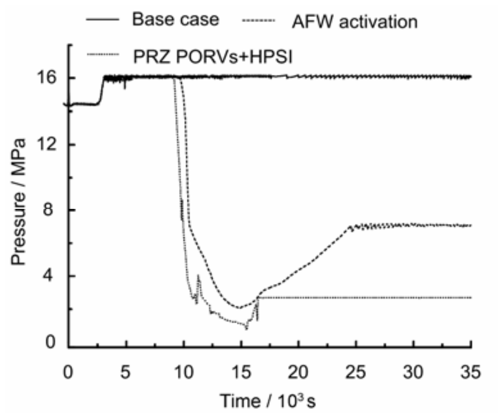
The SBO initial conditions are specified: the plant loses all the power at 0 s.

### 6.1 Description of accident progressions

The accident sequence is shown in Fig.11 and Table 5.




(a) Water level in RPV.




(b) Pressure in pressurizer.

**Fig. 11** Progression of postulated SBO accident and mitigation measures.

**Table 5** Analytical results from SBO accident and measure sequence / s

| Progression | Base case | 1st measure | 2nd measure |
|---|---|---|---|
| Accident begins | 0.0 | 0.0 | 0.0 |
| Reactor trip | 0.0 | 0.0 | 0.0 |
| SG empty | 2775 | 2775 | 2775 |
| Core begins to uncover | 6925 | 6925 | 6850 |
| PRZ PORVs opened manually | / | / | 9150 |
| Core completely uncovered | 8575 | 8575 | 9200 |
| HPIS initiation | / | / | 9600 |
| AFW initiation | / | 9650 | / |
| Accumulator initiation | / | 11850 | 10200 |
| Core melt starts | 11950 | / | / |
| Core reflooded | / | 12175 | 10200 |
| Hot-leg creep rupture | 12475 | / | / |
| Core melt down | 31125 | / | / |
| Lower plenum melts through | 31750 | / | / |
| Consequence of accident and effectiveness of measure | Core melt | Core melt is prevented | Core melt is prevented |

### 6.2 Mitigation measures

Referring to the WOG SAMG, when the temperature of the outlet of the core exceeds 650 °C [5], two measures are considered to take on the SBO base case: 1) initiation of AFW; 2) opening of PRZ PORVs and activation of HPIS to feed the primary system.

#### 6.2.1 AFW activation

When the temperature of the core outlet exceeds 650 °C at about 9650 s, it is assumed that AFW can be activated. As shown in Fig.11, the residual heat in the reactor core can be removed by SG, which decreases the RCS temperature and pressure. When the RCS pressure drops to 5 MPa, the accumulators begin to inject water into the RCS, and the water level in RPV begins to rise. The core is reflooded at 12175 s. The accumulators are empty at about 15075 s. Following this, as the RCS pressure remains lower than the set-point that PRZ PORVs open, the water level in RPV remains above the top of the core, and melting of the core is prevented.

**6.2.2** RCS depressurization and HPIS activation

When the temperature of the core outlet exceeds 650 °C, it is assumed that the PRZ PORVs are opened manually, which decreases the RCS pressure as shown in Fig. 11. When the RCS pressure reaches 10.8 MPa, the HPSI is resumed in time, and the water level in RPV begins to rise. The accumulators are also activated at 10200 s. Finally, the core is reflooded, and the water level in RPV remains above the top of the core. The melting of the core is prevented.

## 7 Conclusions

Using SCDAP/RELAP5, four severe accident sequences (LOCA, ATWS, SGTR, and SBO) in a PWR with 300 MWe are calculated; several measures are considered to mitigate the accident consequences referring to the WOG SAMG and are verified in this article. The results are summarized as follows:

1) The four accidents of LOCA, ATWS, SGTR, and SBO will induce severe consequences, including core damage or core melt and will be a challenge to the integrity of RPV.

2) In the SBLOCA accident combined with the unavailability of HPSI and AFW, the resumption of HPSI may prevent the melting of the core.

3) In the LOFW-ATWS accident combined with the unavailability of AFW, the resumption of AFW and RCS depressurization may prevent the melting of the core.

4) In the SGTR accident combined with the unavailability of HPSI and AFW, simultaneous resumption of HPSI and AFW may prevent the melting of the core ; resumption of HPSI may effectively arrest the progression of core damage ; AFW activation cannot arrest the core damage progression effectively by just minimizing the consequence of the accident; RCS depressurization cannot avoid the melting of the core, but the core will melt at low pressure.

5) In the SBO accident, resumption of AFW may prevent the melting of the core; RCS depressurization and HPSI activation may effectively arrest the progression of core damage.

6) The results of the severe accident study in this article may be referred to the development of SAMG, but the above-mentioned mitigation measures are just an initial study in SAMG. The method of combining these mitigation measures with the practical measures of plants still needs to be discussed, and the validity of the practical measures needs to be verified.

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