Core damage assessment method based on core uncovery time for AP1000 nuclear power plant severe accident

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Abstract: In the event of severe accident in AP1000 Nuclear Power Plant (NPP), timely and accurate assessment of core damage severity can provide the basis for nuclear emergency response actions. There are two popular methods for core damage assessment: Westinghouse Owners Group Core Damage Assessment Guidance (CDAG) which is based on the core exit temperature (CET) and containment radiation monitor readings; and the core damage assessment method which is based on the time that core is uncovered (IAEA-TECDOC-955). The main method used in the Chinese operated AP1000 is developed based on the CDAG. The method proposed in IAEA-TECDOC-955 was for second generation reactors, and whether it is applicable to AP1000 reactors needs further verification. Such verification is the objective of this paper. In this paper, the method in IAEA-TECDOC-955 has been studied. The severe accident induced by Large Break Loss of Coolant Accident (LBLOCA) was selected as a reasonable scenario in this paper, and it was modeled by MELCOR for the verification whether the method is applicable to AP1000 reactor. It can be concluded from the comparative results that the core damage assessment method in IAEA-TECDOC-955 applied in AP1000 is conservative. This conclusion can provide basis for the development of comprehensive core damage assessment system.

Keyword: IAEA-TECDOC-955; uncover time; MELCOR; AP1000; LBLOCA

1 Introduction

During severe accident in NPP, timely and accurate assessment of core damage can provide the basis for nuclear emergency response actions. Early effective decision can obviously improve the effectiveness of nuclear emergency response team, mitigate the progression of severe accident and reduce the loss of personnel and property. The widely-used core damage assessment methods include the method proposed by International Atomic Energy Agency (IAEA) in IAEA-TECDOC-955 [1], the method recommended by American Nuclear Regulatory Commission (NRC) in RTM-96 [2] and the method (CDAG) developed by Westinghouse in WCAP-14696 [3] among others. The assessment method in IAEA-TECDOC-955 uses the time that the core remains uncovered to estimate the core damage state, in addition, the containment radiation monitor readings and the primary coolant isotope concentrations can also provide basis for core damage assessment. The assessment method in NRC's RTM-96 recommends that the core damage state depends on the time that core is uncovered, the containment radiation monitor readings, the primary coolant isotope concentrations and hydrogen concentrations in containment. The Westinghouse's CDAG method (WCAP-14696) uses the core exit temperature and containment radiation monitor readings to evaluate the core damage state.

Chinese Ministry of Environmental Protection Nuclear and Radiation Safety Center proposed a suitable core damage assessment method for both nuclear power plants in operation and under-construction in China, which is a combination of CDAG and the IAEA-TECDOC-955 method, and a detailed top design of the assessment system [4]. This design will play a significant role in the development of the fast core damage assessment system and it is applicable to all the reactors except Qinshan Phase Ⅲ heavy water reactor, high temperature gas cooled reactor (HTGR) and sodium cooled fast reactor (SFR) in China. This method aims to make up for the deficiency of CDAG method, utilizing the time core is uncovered to evaluate the core

Received date: September 27, 2017

damage state. The time that the core is not covered can be obtained by pressure vessel level (PVL). Through the feasibility research by China Institute of Atomic Energy, it is confirmed that the PVL can be used to evaluate the core damage state [5].

The core damage assessment for AP1000 in China are mainly developed based on CDAG method, such as core damage assessment systems for Haiyang NPP and Sanmen NPP. In this paper, the severe accident induced by Large Break Loss of Coolant Accident (LBLOCA) was selected as a reasonable scenario, and it was modeled by MELCOR for the verification of whether the core damage assessment method in IAEA-TECDOC-955 is applicable to AP1000 reactors.

2 Study on the method in IAEA-TECDOC-955 with MELCOR

2.1 Method in IAEA-TECDOC-955

The core damage assessment method as reported in IAEA-TECDOC-955 takes the time that core is uncovered as the main parameter to evaluate the core damage state. Moreover, the containment radiation monitor readings can also provide indications for core damage state. With respect to the application of CDAG method that assess core damage based on containment radiation monitor readings in addition with time, only the core damage assessment based on time that core is uncovered is studied in this paper.

The method of core damage assessment based on core uncovery time is illustrated as follows:

Step 1: Estimate the time at which the top of the core is uncovered. Assume the time at which：

(a) Water level is at the top of active fuel or

(b) PWR primary system temperature is greater than 673K.

Step 2: Estimate the time the core is cooled. Assume the time at which:

(a) Water level is at top of active fuel,

(b) Most of the CETs are less than 573K or

(c) Injection rate into the vessel is greater than the set value.

Step 3: Estimate the time the core is not covered with water using the relation.

$$T_{unc} = T_{cooled} - T_{topunc} \quad (1)$$

Where T_{unc} is the time core remains uncovered, T_{cooled} is the time cooled (step 2), T_{topunc} is time that the top of the core uncovered (step 1).

Step 4: Use Table 1 to determine the potential core damage states.

Step 5: Re-assess whenever there has been a major change in core conditions.

Table 1 Core damage versus time that core is uncovered.

Time that core is uncovered (h)	Estimated core damage
0	Normal coolant
0	Coolant with 10 to 100 times normal isotope concentrations
>0.25	100% gap release
>0.5	10-50% core melt
>1.0	100% melt

2.2 Modeling the parameters with MELCOR

2.2.1 Time that core is uncovered

The water level of the core region changing with time can be calculated with MELCOR. Considering the fact that decay power curve of the core decreases with time, choosing the earlier uncovered part of the core for the study is conservative. In this paper, the upper half of the core is chosen for the study. The uncovered time can be obtained by water level curve which is calculated with MELCOR.

2.2.2 Fraction of core melt

In the model of AP1000, the core region has been divided into four rings in radial orientation and ten levels in axial orientation. Each ring and each level decide one cell, therefore, the core region are modeled by forty cells. It is assumed that there are three damage states for each cell according to the mass of the fuel calculated by MELCOR, partly melt (<50%), semi-complete melt (>50%) and completely melt. For instance, it is assumed that the cell completely melts if the mass of the cell is zero.

2.3 Calculation based on integral code MELCOR

2.3.1 Model of AP1000

Integral code MELCOR [6] is used to establish the model of AP1000 nuclear power plant in this paper. This model couples the calculation between the thermal hydraulic and the transport and release process of the radioactive fission products, which simulates the whole process of severe accident in AP1000 reactor. In the model of AP1000 nuclear power plant, CMT, ACC, ADS, IRWST and ERVC system are modeled. The parameters are obtained from AP1000 FSAR [7]. As illustrated in Fig.1, the AP1000 RCS is modeled by reactor pressure vessel with six nodes, two reactor coolant loops with four cold legs and two hot legs, four reactor coolant pumps, two steam generators with twelve nodes. The turbine, ACC, CMT, pressurizer, direct vessel injection (DVI) lines, IRWST and feedwater system (FW) are respectively modeled by one node. As illustrated in Fig.2, the core active region and lower head are divided into four rings in radial orientation and ten levels in axial orientation. Each ring and each level decide one cell.

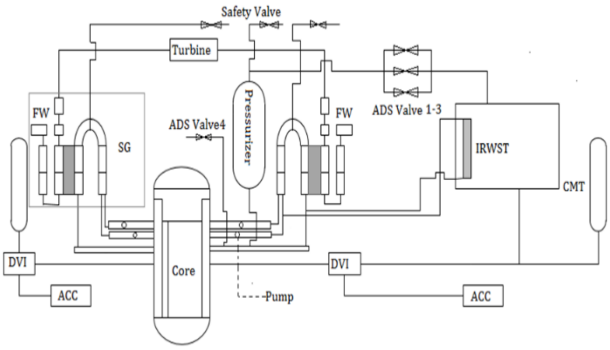

Fig.1. Hydrodynamic nodalization of the AP1000 RCS.

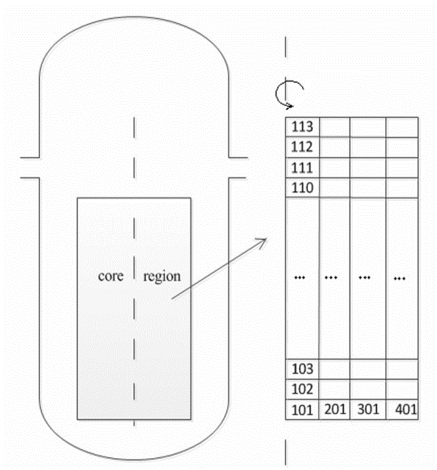

Fig.2. Model of core active region and lower head.

2.3.2 Accident Sequence Selection

Large Break Loss of Coolant Accident (LBLOCA) was selected as a reasonable scenario upon which to base the timing of initial fission product release into the containment with the reason that Loss of Coolant Accidents (LOCAs) are a substantial contributor to Core Damage Frequency (CDF) for PWR according to NUREG-1465 [8]. In this paper, the severe accident initiated by LBLOCA has been chosen for the study. Several assumptions are made as follows: The accident occurs at 0 s, Core Makeup Tank (CMT), Accumulator (ACC) and Automatic Depressurization System (ADS) are available, water in In-containment Refueling Water Storage Tank (IRWST) fails to inject to RPV through DVI lines and Passive Residual Heat Removal System (PRHRS) fails to work.

2.3.3 Accident Progression

Accident progression as calculated by MELCOR is shown as follows. The main coolant pipe double-ended rupture at 0 s. Then the coolant in primary circuit leaks to the containment, leading to the reactor coolant system pressure dropping. At 3.4 s, the reactor shuts down due to the low pressure signal from pressurizer. Then reactor coolant pumps scram, steam turbine trips and CMTs begin to work. At 442 s, ADS begins to work due to the high pressure signal. At 2,295 s, the gap release occurs. At 2,787 s, when the core temperature is up to 2499 K, core begins to melt. At 22,424 s, the lower head fails from creep-rupture due to water in IRWST unsuccessful injection. The key events are listed in Table 2.

Table 2 Key events for LBLOCA

Events	Time (s)
Reactor shut down	3.4
CMT works	5
ACC works	169
ADS works	442
Gap release	2295
Core melt	2787
Lower head failure	22424

3 Results analysis

China Institute of Atomic Energy has confirmed that the PVL can be used to evaluate the core damage state. In this paper, the time that core is uncovered is obtained by PVL.

The verification of the core damage assessment method based on time that core is uncovered proposed by IAEA includes three phases: A phase for the time that core is uncovered larger than 0.25 h, another phase for the time that core is uncovered larger than 0.5 h and the third phase for the time that core is uncovered larger than 1.0 h.

3.1 Phase of time that core is uncovered larger than 0.25 h (first phase).

As depicted in Fig.3, the main coolant pipe double-ended ruptures at 0 s. The level of core active region drops rapidly. Subsequently, the water in CMT and ACC is injected to core region, leading to the water level changing rapidly. This rapid change state lasts to 1260 s. As listed in Table 2, gap release occurs at 2295 s, and the time that core is uncovered is 1035 s. Considering the water level fluctuates wildly before 1260 s, the actual time that core is uncovered is larger than 1035 s. As listed in Table 3, through the comparison with integral code MELCOR, the assessment method proposed in IAEA-TECDOC-955 is conservative during the first phase (time > 0.25h).

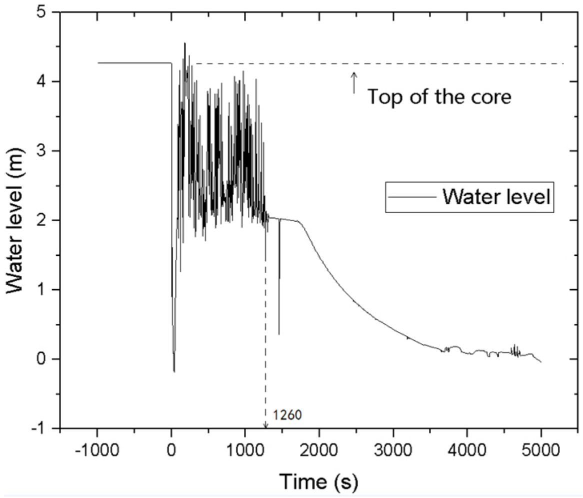

Fig.3. Water level of the core.

Table 3 Gap release.

Method	Time (s)	Gap release
IAEA-TECDOC-955	>900	100% gap release
MELCOR	>1035	Gap release starts

Table 4 Fraction of core melt

Method	Time core is uncovered (s)	Fraction of core melt
IAEA-TECDOC-955	1.0h	100%
MELCOR	1.0h	~65%

3.2 Phase of time that core is uncovered larger than 0.5 h (second phase)

As depicted in Fig.3, the upper half of the core begins to be uncovered at 1260 s. As depicted in Fig.4, the core begins to melt at 2787 s and less than 32.5 percent of the core has melt at 3060 s. 32.5 percent is within the limit of 10 to 50 percent in IAEA-TECDOC-955.

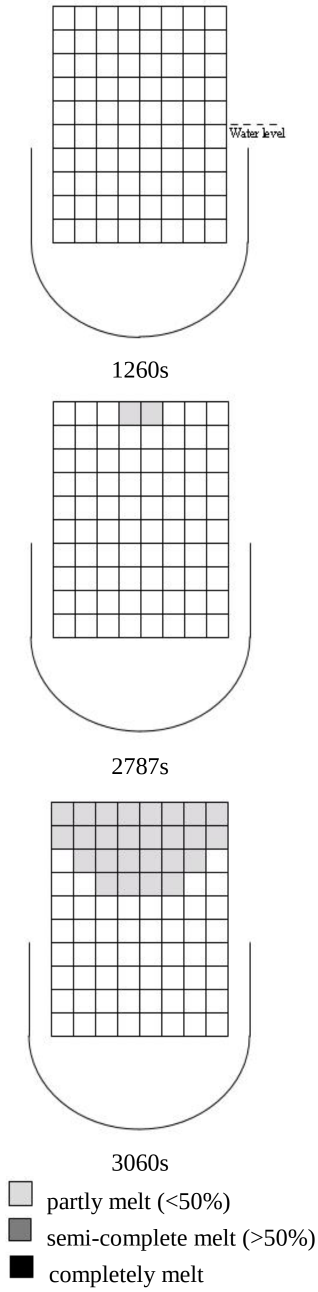

Fig.4. Progression of core melt.

3.3 Phase of time that core is uncovered larger than 1.0 h (third phase)

As depicted in Fig.3, the upper half of the core begins to be uncovered at 1260 s. As depicted in Fig.5, the core begins to melt at 2787 s and about 65 percent of the core has melt at 3060 s. As listed in Table 4, 65 percent obtained by MELCOR is less than the reference value 100 percent in IAEA-TECDOC-955, therefore the assessment method proposed in IAEA-TECDOC-955 is conservative during the phase that time core is uncovered is larger than 1.0 h.

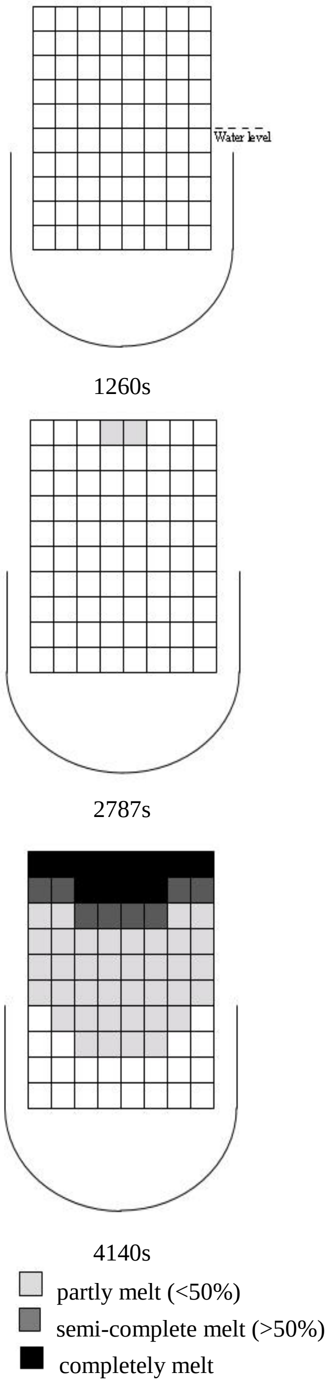

Fig.5. Progression of core melt.

4 Conclusion

In this paper, we performed a comparative analysis between the integral code MELCOR and the assessment method based on core uncovery time in IAEA-TECDOC-955, and we reach the following conclusions:

(1) During the first phase of core uncovery (time that core is uncovered larger than 0.25 h,) the assessment method proposed in IAEA-TECDOC-955 is conservative.

(2) During the second phase (time that core is uncovered larger than 0.5 h), the results calculated with MELCOR is within the limit of 10 to 50 percent in IAEA-TECDOC-955, therefore the range proposed in IAEA-TECDOC-955 is reasonable for AP1000 reactor.

(3) During the third phase (time that core is uncovered larger than 1.0 h), the assessment method based on the time core is uncovered proposed in IAEA-TECDOC-955 is conservative.

These conclusions can serve as a reference for the development of core damage assessment system for AP1000 reactor, based on the method proposed in IAEA-TECDOC-955.

Acknowledgement

This work was supported by the National Science and Technology Projects of China (2013ZX06002001).

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