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Transient analyses for lead–bismuth cooled accelerator-driven system

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ABSTRACT

The transient analyses for the lead–bismuth cooled Accelerator-Driven System (ADS) were performed with the use of the SIMMER-III and RELAP5/mod3.2 codes to investigate the possibility of the core damage. Five accidents; the beam window breakage, the protected loss of heat sink, the beam overpower, the unprotected loss of flow and the unprotected blockage accident were analyzed as the typical accidents in the ADS. Through these calculations, it was confirmed that all calculation results except the protected loss of heat sink satisfied the no-damage criteria. In the protected loss of heat sink, the cladding tube temperature reached at the melting temperature after 20 h although the calculation condition was very conservative. It is required to design a safety system of the ADS to decrease the frequencies of the accidents and to ease the accidents.

1. Introduction

An Accelerator-Driven System (ADS) has been studied to transmute minor actinide (MA) included in the high level waste (HLW) to reduce the burden for the geological disposal of the HLW. Japan Atomic Energy Agency (JAEA) has investigated a lead bismuth eutectic (LBE) cooled ADS. The ADS consists of a high intensity proton accelerator with 1.5 GeV beam energy, an LBE spallation target and a subcritical core with 800 MW thermal power, and it can transmute about 250 kg MA per year (Oigawa et al., 2011; Tsujimoto et al., 2004, 2007). The subcritical core is driven by the spallation neutrons produced in the LBE spallation target and the MAs loaded in the subcritical core are transmuted by the spallation or fission neutrons.

It is considered that the ADS is safer than critical reactors because the ADS is operated in a subcritical state. Since the operation is the subcritical state, (1) its shutdown is easy (just to stop the accelerator) and (2) a possibility of a critical accident is smaller than the conventional critical reactors. For the LBE, the following points are advantages: (1) the boiling point of the LBE is very high (1670 °C). It means there is little possibility of a void generation by boiling. (2) The LBE is inactive against the water, differently from sodium. However, it is very important to control an oxygen concentration in the LBE to protect corrosion and a generation of a lead oxide. It is assumed that the lead oxide will be one of the causes for a flow blockage. Additionally, the following points should be supposed as an inherent issue of the ADS, (1) a beam duct to transport the protons is added as a new structure and (2) a possibility of a beam intensity change should be considered.

Considering such characteristics of the ADS, a preliminary investigation for safety was performed by the Level 1 PSA (Probabilistic Safety Assessment) (Sugawara et al., 2010, 2009). Through this investigation, it was found that probabilities of two cases, Beam Window Breakage (BWB) and Protected Loss of Heat Sink (PLOHS) were more than 10^{-6} [reactor year]. Here, ‘Protected’ means a success of the beam-shutdown and ‘Unprotected’ means a failure of the beam-shutdown. For other events, such as Beam Overpower (BOP) and Unprotected Loss of Flow (ULOF), the Level 1 PSA indicated the frequencies of these events were less than 10^{-6} [reactor year].

Based on the past assessment, some events are chosen as a typical accident in the ADS. This study aims to analyze transients of these accidents to investigate the possibility of a core damage by using two calculation codes, the SIMMER-III (Yamano et al., 2003; Tobita et al., 2006) and the RELAP5/mod3.2 (The Relap5 Development Team, 1995) codes. The SIMMER-III code has been employed to analyze ADS transients (Maschek et al., 2003; Liu et al., 2010) and the RELAP5/mod3.2 code has been used to calculate transients of liquid metal cooled systems (Bandini et al., 2011). In the next section, the ADS plant used in this study is explained. Calculation codes, models and cases are also introduced in this section. Section 3 presents the calculation results, and Section 4 summarizes these results and discusses about the possibility of the core damage.

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2. Calculation conditions

2.1. ADS plant

The calculation was performed for the ADS proposed by JAEA (Saito et al., 2006). Table 1 presents main parameters of the ADS plant. Fig. 1 shows a conceptual diagram of the ADS. The reactor vessel contains a beam duct, a subcritical core, a steam generator and a primary pump (main pump in Fig. 1), mainly. A Primary Reactor Auxiliary Cooling System (PRACS) is prepared to remove a decay heat. However, in this study, the PRACS was not considered to treat the severest case.

As described above, the LBE is used as both the spallation target and the coolant. A nitride fuel of plutonium and MA is cladded by T91 steel. The fuel pins are assembled as a ductless hexagonal fuel assembly (FA), then these FAs are loaded into the subcritical core. The LBE spallation target is separated by a partition wall to avoid the cross-flow from the core to the target region since the ductless FA is used in this system. The thermal power of the subcritical core is 800 MW and the maximum proton beam power is 30 MW. This system can remove 820 MW heat (residual 10 MW is a loss by heat release) and generate 270 MW electricity. This electricity can manage the operation of the proton accelerator.

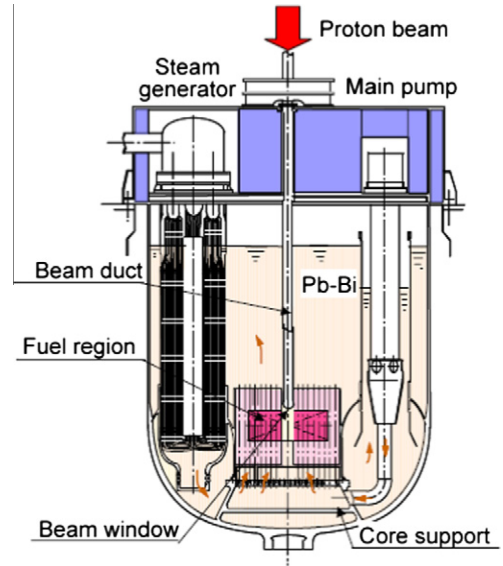

Fig. 1. Conceptual diagram of LBE-cooled ADS.

2.2. Calculation code

2.2.1. SIMMER-III

The SIMMER-III code is an advanced safety analysis code, which has been developed to investigate postulated core disruptive accidents in fast reactors (Yamano et al., 2003; Tobita et al., 2006). The SIMMER-III code is a two-dimensional three-velocity field, multiphase, multi-component, Eulerian fluid dynamics codes coupled with a structure model and a space-, time- and energy-dependent neutron kinetics model. The latest version of the SIMMER-III code is available to analyze the LBE-cooled ADS by adding features to treat the subcritical state with the external neutron source and physical properties for the LBE (Maschek et al., 2000). However, it is unable to treat a heat generation by the spallation reaction in the target region. So, the heat generation in the target region was ignored in the SIMMER-III calculation. It is appropriate to analyze a short-range (a few seconds, for example) transient.

2.2.2. RELAP5/mod3.2

The RELAP5/mod3.2 (RELAP5 in the following) code is a thermal hydraulic computer code, which has been developed to predict the behavior of nuclear plants during transient and accidental conditions (The Relap5 Development Team, 1995). The code models the coupled behavior of the reactor coolant system and the core for loss of coolant accidents and operational transients such as anticipated transient without scram and loss of flow. The module to use the LBE as coolant were prepared (Saito et al., 2006) and employed in this study. The code is able to treat whole flow of a system including secondary cooling system but is unable to use the neutronic calculation. It is adequate to calculate a long-range (several hours, for example) transient.

Table 1
Main parameters of the ADS plant.

Thermal power	800 MW
Proton beam energy	1.5 GeV
Max. beam current (power)	20 mA (30 MW)
Operation time (1cycle)	600EFPDs[a]
Spallation target	LBE
Coolant	LBE
Fuel	TRU nitride fuel
Cladding tube	T91 steel
Type of fuel assembly	Ductless and hexagonal
Reactor vessel	Tank type
Number of primary pump	2
Number of steam generator	4
Number of PRACS	3
Quantity of heat removal	820 MW
Quantity of heat removal by one PRACS	5 MW
Electric-generating capacity	270 MW

[a] Effective full power days.

2.3. Calculation model

2.3.1. SIMMER-III

Although the subcritical core consists of the hexagonal FA, the SIMMER-III code is unable to treat such hexagonal model. Then, the subcritical core was changed to an RZ calculation model as shown in Fig. 2. The subcritical core consists of 84 FAs that are divided to four rings. The most inner one is named as the 1st ring, the next one is the 2nd ring and so on. These zones were used in the investigation of a multi-zoned ADS by Nishihara et al. (2008), and in this study, a two-zoned model which has two different plutonium enrichment is employed. Figs. 3 and 4 illustrate the RZ calculation models of the ADS plant as conceptual one and actual-size one, respectively.

Table 2 shows the parameters for the SIMMER-III calculation model. For the fuel, the nitride fuel is employed in this design. The thermal conductivity and heat capacity of the nitride fuel studied by Nishi et al. (2011) are referred. For the gap conductance between the fuel pellet and the cladding tube, the default value (5678.26 [W/m^2 K]) prepared in the SIMMER-III code is used. For the coolant, temperatures at the inlet and outlet of the core are 300 °C and 400 °C, respectively. A nominal velocity of the LBE in the core region is 2.0 m/s.

When the subcriticality is large, the importance of the fission reaction near the spallation target increases. It means the cladding tube temperature at the nearest position from the spallation target becomes maximum at this moment. In the reference (Nishihara et al., 2008), it was found that the power distribution in the 2nd EOC (End of Cycle) was the severest state since the subcriticality in the 2nd EOC was the largest during the ADS operation as shown in Fig. 5. Based on this result, a neutronic calculation model in the 2nd EOC state was employed. In the neutronic calculation, an