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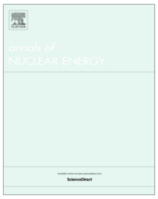

An accident-tolerant control drum system for a small space reactor

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ABSTRACT

In this paper, an accident-tolerant control drum system was proposed to enhance the safety of space reactors in various launch accidents and the safety enhancement was demonstrated for a LEU-fueled and a HEU-fueled space reactors. The space reactors with an accident-tolerant control drum system remain subcritical even when all the control drums are missing while the reactors with a control rod system become supercritical when a control rod is missing without any damage in reflector. The heterogeneous LEU-fueled space reactor with an accident-tolerant control drum system remains subcritical even when it is immersed in dry sand, wet sand, or water with two adjacent control drums are rotated to the operation position. The HEU-fueled space reactor with an accident-tolerant control drum system remains subcritical even when it is immersed in various surrounding materials with one or two control drums rotated to the operation position depending on the thickness of the reflector. Besides the safety enhancement, a reduction of the total reactor mass was achieved by adopting an accident-tolerant control drum system instead of a control rod system.

1. Introduction

A power supply system of a spacecraft plays a key role in deep space exploration and the only practically applicable option for the power supply of a spacecraft exploring beyond Jupiter or out of the solar system is nuclear energy (Lee et al., 2015). Since SNAP-10A launched in 1965, many small fission reactors for power supply of a spacecraft have been developed. Recently, a small fission reactor with a fast spectrum, KRUSTY, has been developed by the United States (US) National Aeronautics and Space Administration (NASA) and Los Alamos National Laboratory (LANL) for deep space mission, where highly enriched uranium (HEU) is used as fuel (Poston et al., 2013). A small thermal reactor with low enriched uranium (LEU) fuel is being studied at Korea Atomic Energy Research Institute (KAERI) as a possible electric power supplier for deep space probe (Lee et al., 2015). A control rod (CR) system was adopted as the reactivity control system of the reactors in the study and the reactors in the study were designed so that they remain subcritical when they were immersed in water, wet sand or dry sand regardless of whether they had no or minor damage (as launched or coolant pipes broken) or they had major damage (reflector and some of control rods are missing). However, it is inevitable for the reactors with a control rod system to become supercritical in "the worst-case accident scenarios" in which the control rods are missing without any damage in the reflector (Lee et al., 2015).

Besides the control rod system which has been widely used for nuclear reactors since Chicago Pile-1, many concepts of reactivity control system for space reactor such as the control drum (CD) system (Barkov, 1967), the sliding reflector or the control shutter concept (Bost, 1973), and the hinged reflector or the petals reflector concept adopted in SP-100 space reactor (Deane et al., 1989) have been proposed and studied widely (Poston, 2001; King et al., 2006; El-Genk, 2009; Craft et al., 2011; Bragg-Sitton et al., 2011). As mentioned above, the loss of control rods during launch accidents inevitably results in an increase of core reactivity and so does the loss of control drums. In case of a reactor with a sliding reflector or hinged reflector system, on the contrary, the loss of the reactivity control system (the reflector itself) results in a decrease of core reactivity. However, the reflector can accidently move to its operation position when there is an external impact on the reactor. For example, a crash on the ground can move the sliding or hinged reflector to its operation position due to the inertia of the reflector or the core. With any of the reactivity control system mentioned above, the event in which the reactor becomes supercritical is still likely to happen though the absolute value of the probability is relatively small.

In this paper, an accident-tolerant control drum (ATCD) system is proposed as the reactivity control system of a space reactor to resolve the criticality problems during the launch accidents. The

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neutronic performance of the accident-tolerant control drum system was investigated when it was adopted in a LEU-fueled and a HEU-fueled small space reactor. All calculations were performed using a Monte-Carlo code, McCARD (Shim et al., 2012) with continuous energy ENDF/B-VII.0 cross-section libraries.

2. The accident-tolerant control drum system

2.1. Concept of the accident-tolerant control drum system

Fig. 1 compares the concept of conventional control drum system and the accident-tolerant control drum system proposed in this study. In the conventional control drum system, the control drums each of which is consist of poison or absorber part and reflector part are placed in the reflector region. The absorber part of the control drums is faced to the core when the reactor is shutdown while the reflector part of the drums is faced to the core when the reactor is in operation. In the accident-tolerant control drum system, on the other hand, the control drums contain not only the absorber and reflector parts but also fuel part which comprises the reactor core when the drums are in operation position. The absorber part is inserted deep into the core and the fuel part is moved to a position far from the core when the drums are in shutdown position, which results in a large drum worth. Fig. 2 shows the details of an accident-tolerant control drum. In this study, it was assumed that the axis of the control drum is located on the cylindrical core boundary and that the reflector and the absorber are separated by an imaginary coaxial cylinder as well. The fuel part, the reflector part, and the absorber part are wrapped with a thin metallic can. The outer radius of the can is slightly smaller than the control drum hole and there is a thin gap between the control drum and the wall of the control drum hole so that the drum can rotate to start the reactor.

In case of a reactor with the conventional control drum system, the reactivity will increase when the reactor is immersed in water or wet sand with the control drums missing without any damage in reflector as it was in case of a reactor with a control rod system. In case of a reactor with the accident-tolerant control drum system described above, on the contrary, a small reactivity increase or even a reactivity decrease can be achieved in the same situation because the loss of control drum results in a loss of fuel as well as the absorber.

2.2. Performance of the accident-tolerant control drum system in a LEU-fueled space reactor

Two LEU-fueled space reactors with an accident-tolerant control drum system were designed to investigate the performance of the accident-tolerant control drum system. The first case, case A, has a homogeneous core configuration while the second case, case B, has a heterogeneous core configuration in which 20 fuel plates and 21 moderator plates are stacked one after the other as in the LEU-fueled space reactors with a control rod system presented in our previous work (Lee et al., 2015). Most of the design parameters are the same for the two cases but the core radius and the reflector thickness of the homogeneous case are slightly larger than those of heterogeneous case and thus the heat pipe positions are slightly different. Fig. 3 illustrates the top view and side view of the two reactors and Table 1 lists the details of the design parameters. The reactors with an accident-tolerant control drum system have smaller total reactor mass (168.5 kg and 159.3 kg for homogeneous case and heterogeneous case, respectively) than that of the reactors with a control rod system in our previous work (240.8 kg, and 187.1 kg, respectively). The mass reduction is attributed to the fact that there is no control rod hole in the core which increases critical core radius and in turn increases the reactor mass.

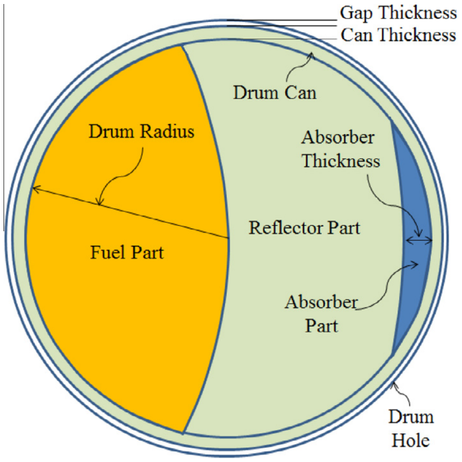
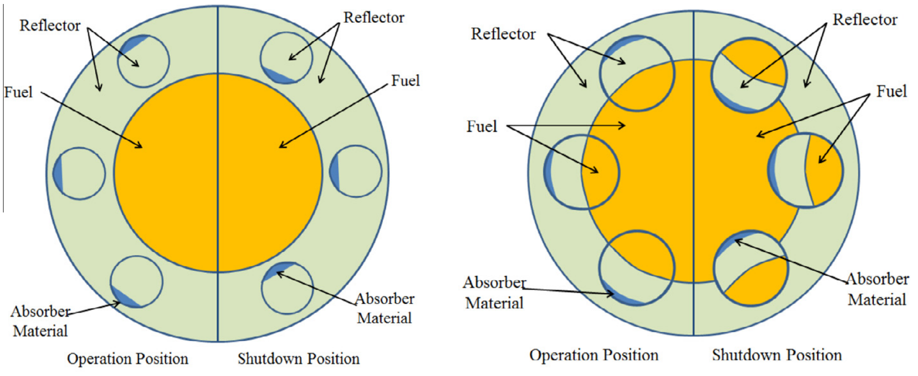


Fig. 2. Details of an accident-tolerant control drum.

Table 2 shows the neutronic performance of the reactors during their life time and we can find that the reactors have similar neutronic performance to that of the reactors with a control rod system in our previous work except for the cold zero power (CZP) shutdown state. The control drum worth is about 33,000 pcm and 44,000 pcm for case A and B, respectively, while control rod worth was about 16,000 pcm for both cases with a control rod system in our previous work. The relatively large total drum worth is achieved not only because a large amount of absorber is inserted deep into the core but also because some fuel is moved to a



(a) Conventional Control Drum System (b) Accident-tolerant Control Drum System

Fig. 1. Comparison of a conventional and an accident-tolerant control drum system.