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Rapid Communication

Infinite multiplication factor of low-enriched UO_2-concrete system

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The possibility of criticality of fuel debris in a form of UO_2-concrete mixture is evaluated by calculating the infinite multiplication factor (k_∞) for a study of criticality control on the fuel debris generated through the molten core concrete interaction (MCCI) in a severe accident of a light water reactor (LWR). The infinite multiplication factor can be greater than unity, which means that handling of the mixture is subject to criticality control. This paper shows that concrete provides efficient neutron moderation and points out the necessity of further investigations on the criticality of UO_2-concrete system for actual handling of fuel debris.

KEYWORDS: fuel debris, infinite multiplication factor, low enriched uranium, uranium dioxide, concrete, MCCI

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1. Introduction

In the case of a severe accident of a light water reactor (LWR), especially when a molten core penetrates a pressure vessel and drops down to the concrete pedestal floor of the containment vessel, it is highly probable that a mixture of damaged fuel and concrete has been generated through the molten core concrete interaction (MCCI). It has been reported that the critical concentration of a mixture of silicon dioxide (SiO_2), which is one of the major materials of concrete, and metal ^{235}U in an infinite system is smaller than that of a ^{235}U-water system due to the small neutron absorption of SiO_2[1]. Another report concludes that concrete is also an effective reflector in thermal neutron systems[2]. As mentioned above, concrete is mainly composed of SiO_2; moreover, it contains light elements which are important from the viewpoint of criticality, *e. g.*, hydrogen and carbon. The results of Ref. 1 suggest that concrete is an effective moderator in high ^{235}U enriched, UO_2-concrete system. Ref. 1 and Ref. 2, suggest that concrete may also be an efficient moderator with low ^{235}U enriched, UO_2 fuel. The authors, accordingly, have started a study on nuclear characteristics of a low ^{235}U enriched, UO_2-concrete system considering normal concrete, the composition of which is realistic, from the viewpoint of criticality control in fuel debris handling.

Focusing on a boiling water reactor (BWR), the possibility of criticality of the UO_2-concrete system was evaluated by calculating its infinite multiplication factor (k_∞) considering the reactivity effect from burn-up. This paper shows some conditions of the system where the k_∞ is greater than unity, and rough estimations of their critical masses.

2. Infinite multiplication factor

2.1. Calculation

Infinite multiplication factors were calculated using an infinite lattice of a sphere cell. As shown in **Figure 1**, the sphere cell is composed of an inner fuel sphere and an outer moderator shell. For the comparison of the reactivity effect from burn-up including the neutron absorption effects of fission products (FPs), three types of fuel were considered: fresh fuel, BWR spent fuel without FPs, and BWR spent fuel with FPs. The fresh fuel has a ^{235}U enrichment of 5 wt.%, and contains no burnable poison. The BWR spent fuels have a burn-up which gives the highest reactivity in its burn-up history considering burnable poison (gadolinium). The burn-up calculation of the spent fuel is described in detail below. The FPs were selected mainly due to their attributes which are important from the viewpoint of criticality safety, *e. g.*, neutron absorption effect[3]. Atomic number densities of those fuel types are listed in **Table 1.** Two types of moderator were considered: normal concrete[4] and water. Their atomic number densities are shown in **Table 2**. Temperature of the fuels and moderators are set to be 25 °C.

Fig1
Table1
Table2

The infinite multiplication factor was evaluated by varying the ratio of moderator volume (V_{m}) to fuel volume (V_{f}) (hereinafter, $V_{\mathrm{m}}/V_{\mathrm{f}}$) and radius of the inner fuel sphere r. These parameters were surveyed to find a condition that gives the largest value of k_∞ on moderation for concrete, and then the latter parameter was varied to study of the effect on heterogeneity (thermal neutron utilization) for UO_2-concrete system. Radii of the inner fuel sphere and the outer moderator shell were varied together keeping the $V_{\mathrm{m}}/V_{\mathrm{f}}$ constant.

Calculations of k_∞ were conducted with a collision probability method using the SRAC code system[5] (PIJ-PEACO module) and a 107-group cross section data based on the nuclear data library JENDL-3.3[6], which is provided with the SRAC code.

The burn-up calculation of the BWR spent fuel was carried out using the SWAT burn-up code system[7]. An 8×8 Step-2 BWR fuel assembly[8] was irradiated under specific power of 25.6 MW/t and cooled for 5 years. The void fraction was set to be 70 % during burn-up. The reactivity of a BWR fuel assembly varies as burn-up progresses. The burn-up of the BWR spent fuel was set to be 12 GWd/t, which gives the highest reactivity in its irradiation history[8].

Additionally, neutron energy spectrum in the moderator and energy dependency of fission in the fuel was calculated to confirm neutron moderation in the UO_2-concrete system. The calculation was done using the continuous-energy Monte-Carlo code MVP[9] and

JENDL-3.3.

2.2. Result

Variation of k_∞ with heterogeneity (radius of the inner fuel sphere, r) under the condition that gives the largest value of k_∞ (V_m/V_f =7.0) is shown in **Figure 2 (1)**. The largest value of k_∞ is observed when r becomes 1.0 cm. The value of k_∞ decreases as the value of V_m/V_f deviates from the optimum value (V_m/V_f =7.0) when r is 1.0 cm. Two typical variations of k_∞ in smaller V_m/V_f (=2.9) and in larger V_m/V_f (=11.0) are also shown in **Figures 2 (2) and 2 (3)**, respectively. These figures also show k_∞ of UO_2-water system for comparison. In Figure 2 (1), there can be seen that k_∞ is greater than unity for those three fuel types when r is several centimeters or smaller, namely, at lower heterogeneity. At higher heterogeneity, the value of k_∞ decreases as r increases because the inner fuel sphere is isolated from nearby fuel spheres by moderator. A similar variation can be seen in Figures 2 (2) and 2 (3), which indicates that the system can be in critical state under the abovementioned conditions on moderation and heterogeneity. The estimation of critical mass is described in Sec. 3.

Fig2(1)

Fig2(2)

Fig2(3)

In comparison with the UO_2-water system, the reactivity effect of replacing concrete with water is positive at lower heterogeneity (small value of r). However, the decrease of k_∞ on UO_2-water system begins at smaller r than UO_2-concrete system, it can be supposed to be mainly due to difference of neutron isolation capability between water and concrete. It is suggested that concrete can be a better moderator than water at higher heterogeneity (large value of r).

Additionally, **Figures 3 (1) and 3 (2)** show neutron energy spectrum in the outer moderator shell and energy dependency of fission in the inner fuel sphere of the UO_2-concrete system, respectively. The value of V_m/V_f and radius of the inner fuel sphere, r, are set to the abovementioned condition that gives the largest value of k_∞. Neutron energy spectrum and energy dependency of fission of a UO_2-water system under the same condition is also shown for comparison. In Figure 3 (1), a small but noticeable peak of thermal neutrons is observed for a UO_2-concrete system, and in Figure 3 (2), thermal fission is dominant over fast fission in a UO_2-concrete system, similar to a UO_2-water system, *i.e.*, concrete is found to be an efficient neutron moderator.

Fig3(1)

Fig3(2)

3. Rough Estimation of Critical Mass

3.1. Calculation

The critical mass for the UO_2-concrete system was estimated under the condition that gives the largest value of k_∞ described in Sec. 2, that is, the value of V_m/V_f and radius of the inner fuel sphere, r, are set to be 7.0 and 1.0 cm, respectively. Three types of fuel are considered as described in Sec. 2: the fresh fuel, the BWR spent fuel without FPs and the BWR spent fuel with FPs. Minimum critical masses of mixture of the fuels and concrete were estimated by varying radius R of a finite heterogeneous sphere which is modeled by clipping a sphere from the infinite lattice as shown in **Figure 4**. The finite sphere is surrounded by 40-cm-thick concrete as a full reflector[10], and the reflector is enclosed by perfect (black) absorber. This calculation was carried out using MVP and JENDL-3.3.

Fig4

3.2. Result

The critical radii and masses of the UO_2-concrete system are summarized in **Table 3**. The critical radii for the fresh fuel, the BWR spent fuel without or with FPs are 42 cm, 55 cm and 71 cm, respectively. Fuel quantities at those critical radii correspond to approximately 0.4 tU, 0.8 tU and 2 tU, respectively. The critical mass of the fresh fuel is doubled by consideration of the actual design of BWR fuel, the burn-up of 12 GWd/t, and with no FPs. The reactivity effect of FPs gives another doubling of the critical mass.

Table3

A typical BWR fuel assembly contains approximately 0.17 tU of fresh fuel and the total amount of fuel in a whole reactor core is approximately 70 tU or more. Although the evaluated critical masses are up to several times as much as the content of a fuel assembly, they are much smaller than that of a whole core. Consequently, the possibility of criticality accident of fuel debris in a form of UO_2-concrete mixture must not be excluded unless other key factors that cause the mixture to remain in the subcritical state are found in further investigations. Moreover, in actual situations, fuel debris is submerged in water, and the composition of concrete could be influenced by the process of the MCCI. Studies considering those situations are also needed for the handling of fuel debris.

4. Conclusion

The characteristics on criticality of a low ^{235}U enriched, UO_2-concrete system are being studied considering such a severe accident of an LWR that its molten core contacts with concrete. Calculation shows the following results: (1) There are some conditions where k_∞ of the UO_2-concrete system can be greater than unity. (2) Thermal fission is dominant over fast fission. These results are ascribed to the moderation capability of concrete.

Even when considering a burn-up with reactivity effect of FPs, the critical mass of the UO_2-concrete system can be as small as 2 tU. The quantity is much smaller than the total amount of fuel in a whole reactor. Therefore, further investigation is needed to find key factors which make the UO_2-concrete system in subcritical state.

The criticality control considering the key factors is important in the handling of fuel debris in a form of UO_2-concrete mixture. The key factors could be water content in the mixture under a submerged condition, neutron poison content in the fuel debris originated from control rods, and so on. Their reactivity effect should be evaluated by sensitivity analyses, and the actual values of those factors must be confirmed by sample taking and measurement of the fuel debris.

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Figure Captions List

Figure 1 Sphere cell for calculation of infinite multiplication factor.

Figure 2 (1) Infinite multiplication factor of UO_2-Concrete system (V_m/V_f=7.0).

Figure 2 (2) Infinite multiplication factor of UO_2-Concrete system (V_m/V_f=2.9).

Figure 2 (3) Infinite multiplication factor of UO_2-Concrete system (V_m/V_f=11.0).

Figure 3 (1) Neutron energy spectra of UO_2-concrete and -water system in moderator.

Figure 3 (2) Energy dependency of fission.

Figure 4 Calculation model for finite heterogeneous sphere.

Table 1 Atomic number density of fuel

Nuclide	Atomic number density ($\times 10^{24}$ atoms/cm^3)		
	Fresh fuel	Spent fuel* without FPs	Spent fuel* with FPs
^{234}U	-	6.9825×10^{-6}	6.9825×10^{-6}
^{235}U	1.1757×10^{-3}	6.2168×10^{-4}	6.2168×10^{-4}
^{238}U	2.2057×10^{-2}	2.2393×10^{-2}	2.2393×10^{-2}
^{nat}O	4.6465×10^{-2}	4.6983×10^{-2}	4.6983×10^{-2}
^{238}Pu	-	2.8950×10^{-7}	2.8950×10^{-7}
^{239}Pu	-	9.1638×10^{-5}	9.1638×10^{-5}
^{240}Pu	-	1.5755×10^{-5}	1.5755×10^{-5}
^{241}Pu	-	5.2453×10^{-6}	5.2453×10^{-6}
^{242}Pu	-	6.7431×10^{-7}	6.7431×10^{-7}
^{241}Am	-	1.5322×10^{-6}	1.5322×10^{-6}
^{95}Mo	-	-	1.7814×10^{-5}
^{99}Tc	-	-	1.7775×10^{-5}
^{103}Rh	-	-	1.0233×10^{-5}
^{133}Cs	-	-	1.9503×10^{-5}
^{143}Nd	-	-	1.5032×10^{-5}
^{145}Nd	-	-	1.0676×10^{-5}
^{147}Sm	-	-	4.1588×10^{-6}
^{149}Sm	-	-	1.1729×10^{-7}
^{150}Sm	-	-	3.4526×10^{-6}
^{152}Sm	-	-	1.6767×10^{-6}
^{153}Eu	-	-	9.9686×10^{-7}
^{155}Gd	-	-	9.8586×10^{-7}

* burn-up of 12 GWd/t

Table 2 Atomic number density of moderator

Element*	Atomic number density ($\times 10^{24}$ atoms/cm^3)	
	Concrete[4] (2.3 g/cm^3)	Water (0.997045 g/cm^3)
H	1.3742×10^{-2}	6.6658×10^{-2}
O	4.5921×10^{-2}	3.3329×10^{-2}
C	1.1532×10^{-4}	-
Na	9.6397×10^{-4}	-
Mg	1.2389×10^{-4}	-
Al	1.7409×10^{-3}	-
Si	1.6617×10^{-2}	-
K	4.6054×10^{-4}	-
Ca	1.5026×10^{-3}	-
Fe	3.4507×10^{-4}	-

* Isotopic abundances are natural.

Table 3 Estimated critical mass of UO_2-concrete system

Fuel Case	Critical radius of heterogeneous sphere *R* (cm)	Critical mass (tU)
Fresh fuel	42	0.4
Spent fuel without FPs	55	0.8
Spent fuel with FPs	71	2

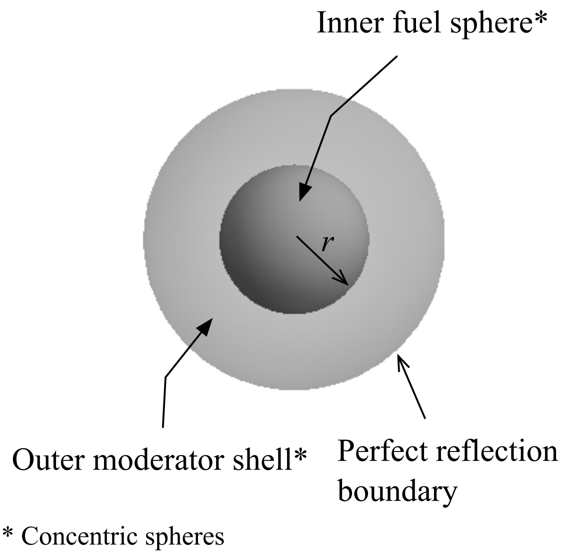

Figure 1 Sphere cell for calculation of infinite multiplication factor.

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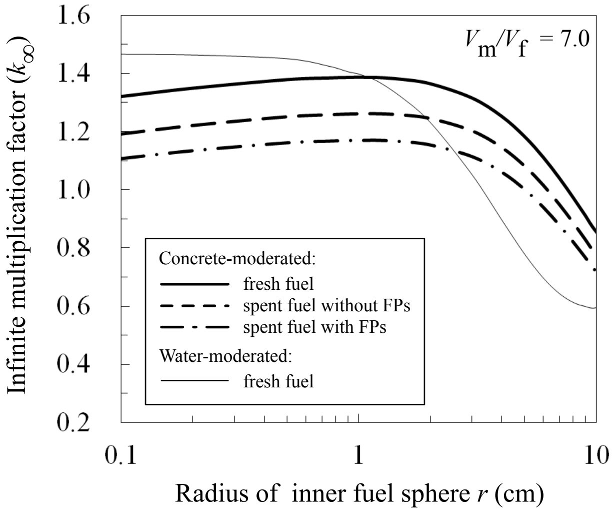

Figure 2 (1) Infinite multiplication factor of UO_2-Concrete system ($V_m/V_f = 7.0$).

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Infinite Multiplication Factor of Low-Enriched UO_2-Concrete System

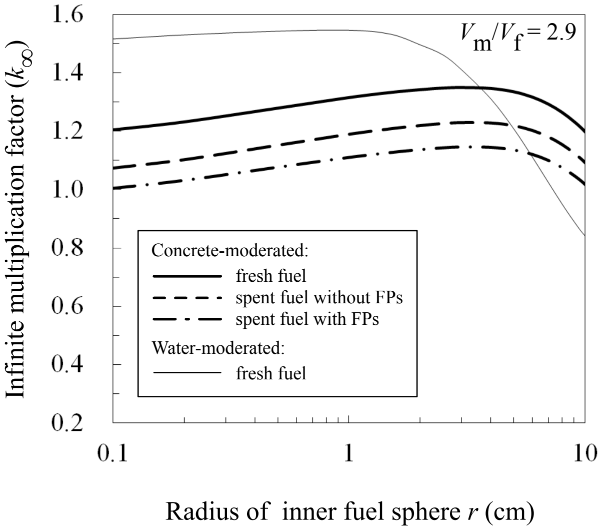

Figure 2 (2) Infinite multiplication factor of UO_2-Concrete system ($V_m/V_f = 2.9$).

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Infinite Multiplication Factor of Low-Enriched UO_2-Concrete System

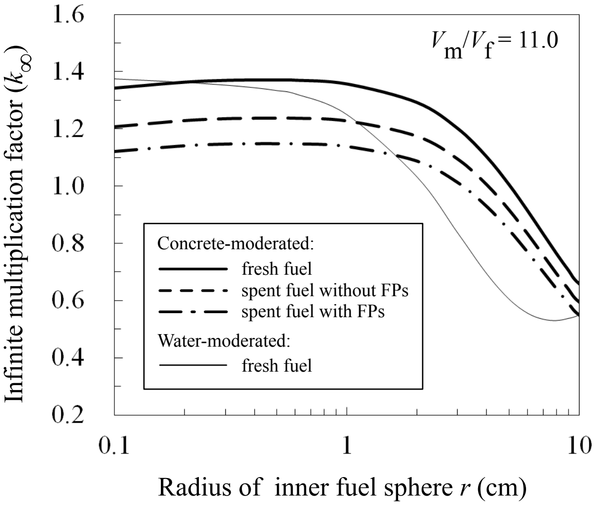

Figure 2 (3) Infinite multiplication factor of UO_2-Concrete system (V_m/V_f = 11.0).

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Infinite Multiplication Factor of Low-Enriched UO_2-Concrete System

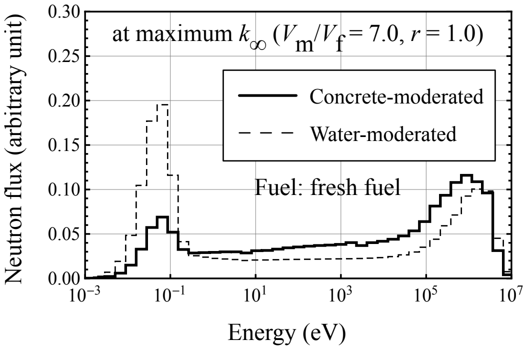

Figure 3 (1) Neutron energy spectra of UO_2-concrete and -water system in moderator.

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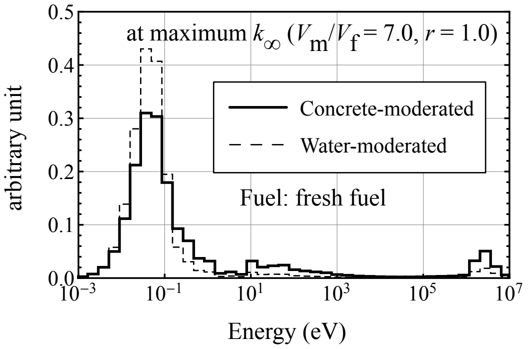

Figure 3 (2) Energy dependency of fission.

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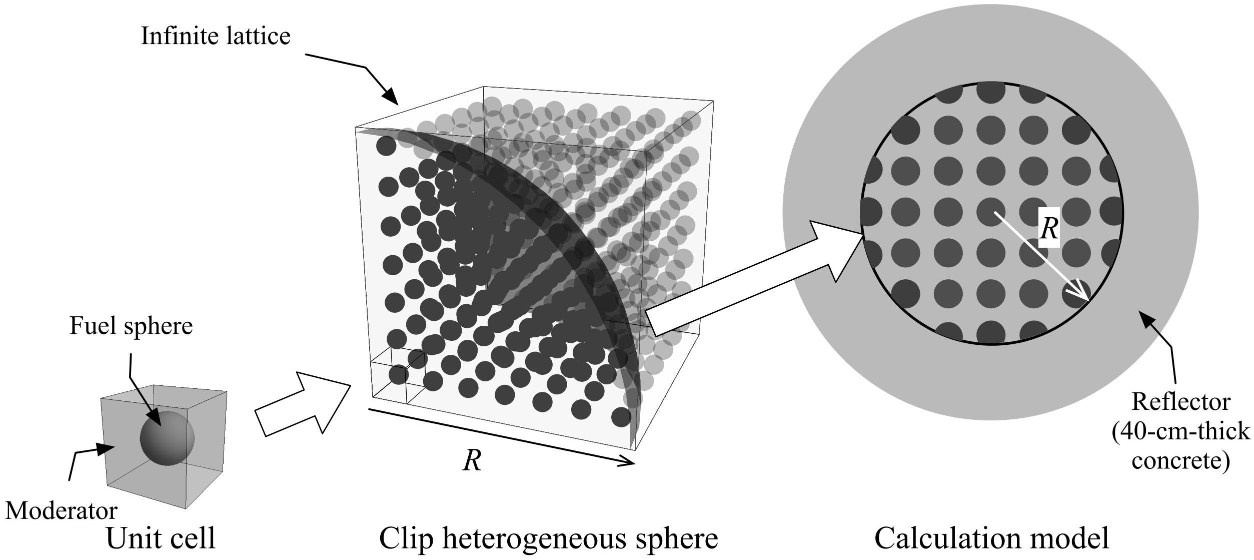

Figure 4 Calculation model for finite heterogeneous sphere.

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