Criticality Concerns on Transportation of a Small Modular Marine Reactor

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1. Introduction

Many transportable small-sized modular reactors are being developed around the world, including SSTAR of the United States, 4S of Japan, and KLT of Russia. The biggest advantage of them is that it can be transported from the factory to the site where no infrastructure has been built. If the reactor vessel itself can still be transported to handle spent nuclear fuel after shutdown, it would be additional benefit not only improving nuclear proliferation resistance but also eliminating the need to install additional nuclear fuel reloading facilities. In particular, if small sized LFRs as power sources for ice-breakers can be carried out long-term mission without replacing fuel and disposed as a whole core, we can expect a feasibility with additional benefits in improvement of proliferation resistance as well as life-cyle safety. However, it is necessary to carefully evaluate criticality whether it is possible to transport all the spent nuclear fuels as loaded in the reactor vessel itself. We may expect high excess reactivity because of higher fissile density even in the spent fuel, because reactor core should have very high initial reactivity for a longer cycle and higher conversion ratio should be achieved. In this study, a LFR core as power source for commercial ice-breakers was designed and examined for the criticality safety of core containing spent fuels under the possible transportation conditions.

2. Nuclear Design Concept

2.1 Reference Core Model

Considering the use of off-the-shelf spent fuel transportation casks, it was determined that reactor core should be smaller than the cylindrical space of 2m radius and 2m height.

Design specifications were adopted from previous studies which is similar to conventional fast reactor core design without blanket. Fuel cycle analyses were performed with the REBUS-3 code system and also assembly design parameters were iteratively determined to meet target core performance.

Fig.1 show the radial core layout of the 60 MWth U-Zr metal fuel core. This design option was found after parametric study and optimization procedure. Core consists of 199 sub-assemblies; 86 drivers, 42 reflectors, 66 radial shields, 6 primary controls and 1 secondary control. Each fuel assembly consists of 271 fuel pins and have total length of 450 cm with the active core height is 175 cm. The reactivity swing was calculated to be 500 pcm while meeting the cycle length with an equivalent radius of 157.5 cm and 175 cm for height.

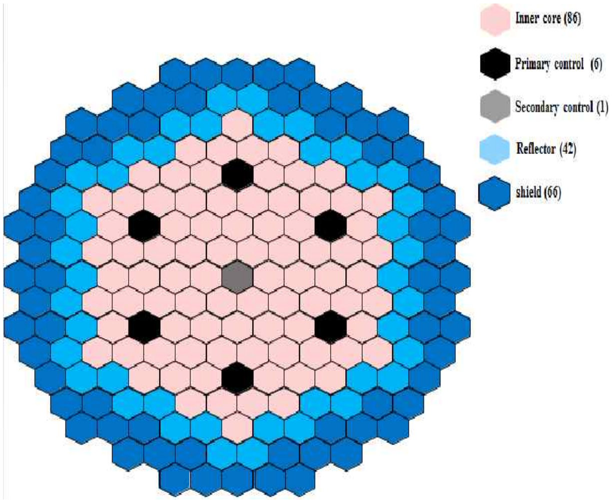

Fig. 1. Radial core layout of reference design

Table I: Primary design and core volume fractions.

Fuel pin	
fuel material	U-Zr metal
smear density, %	65
enrichment, %	12.25
pin gap size, cm	0.1134
pin diameter, cm	0.81
pin pitch, cm	0.9234
cladding thickness, cm	1.14
cladding material	15-15Ti
Fuel Assembly	
duct material	Mod. HT-9
# of pins in an assembly	217
# of fuel assemblies	112
assembly gap, cm	0.4
assembly pitch, cm	15.719
assembly area, cm^2	213.986
Volume fraction	
fuel, %	49.96
structure, %	18.10
coolant, %	31.94

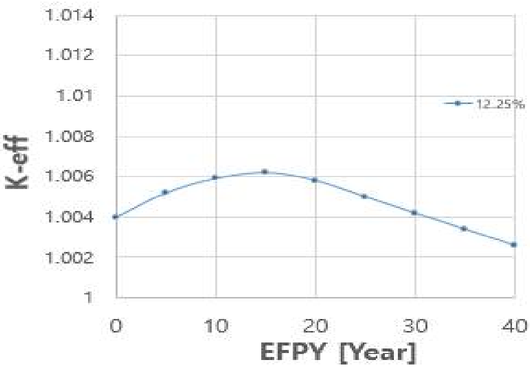

Fig. 2. K-eff letdown curve for life-cycle

2.2 Criticality Evaluation Model and Assumptions

In this study, the three dimensional geometry was modeled and the multi-group transport equation was resolved to calculate the effective multiplication factor by using MCNP6 computer code and ENDF/B-V cross-sectional library.

Size of the fuel storage area inside of vessel is 87.24 cm in radius and 452.32 cm in height. 10 cm thickness of lead lid installed in upper cask body and another 13 cm thickness of carbon steel lid is above it as a cask seal cover. Also bottom of cask consist of carbon steel in 23 cm thickness. For a cask shielding, three-layer confinement vessel is modeled as carbon steel, resin and carbon steel.

The vacuum boundary conditions were applied at the outside surface of cask.

For the transportation of spent nuclear fuel in accordance with the provisions of 10 CFR71, the double-contingency principle should be applied to satisfy the effective multiplication factor of 0.95, even in normal and accident conditions.

Therefore evaluation scenarios were chosen for both fresh fuel and spent fuel in criticality analysis assuming that all fuel assemblies are transported as a whole core inside of the transportation cask.

One of the double contingency, the optimum moderation condition was analyzed with variation of water density under the complete immersion conditions. For the engineering solution, insertion of boral plate along the cask wall was checked also.

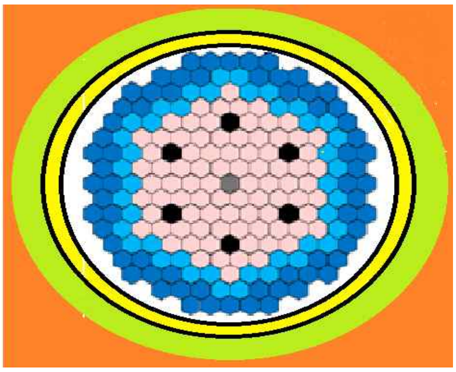

Fig. 3. Reference Cask Design

2.3 Criticality Evaluation Result

1. Complete immersion conditions

The first accident scenario assumed that all empty space inside the cask area was filled with water. In this case water acts as a moderator and the effective multiplication factor is likely to increase. Also a parametric study was carried out in order to find the optimum moderation condition by changing water density from 0 to 1 with 0.2 intervals. As a result when the water density is 0.6 g/cm3, the highest effective multiplication factor was calculated for 1.13632, which exceed the regulatory standard about 18% Δk. This means that moderation effect of water is quite large and sensitive in criticality. In case of core design for ice-breaker, hypothetical accident condition such as water immersion with leak of Pb-Bi coolant leakage should be considered in detail.

Table Ⅱ: Change of k-eff with different moderator conditions

	water density [g/cm^3]	K-eff	Standard deviation [%]
Case-1	vacant	0.81324	0.021
Case-2	0.2	1.03292	0.031
Case-3	0.4	1.12256	0.029
Case-4	0.6	1.13632	0.029
Case-5	0.8	1.11332	0.029
Case-6	1.0	0.94155	0.027

2. Case of fissile content change due to breeding and burnup

In the case of PWR, the reactivity tends to decrease continuously during the operation, while ultra-long cycle core should have a very small reactivity swing and can have the highest reactivity in the middle of life cycle. As shown in Figure 2, a designed core has a very flat k-eff slope in which reactivity swing is less than 500 pcm throughout the whole cycle. Therefore, burnup credit effect is not significant and rather at the middle of the cycle reactivity exceeds the initial reactivity. In order to understand the impact of fissile content change during burnup, criticality evaluation was done for the different burnup stages; BOC, MOC and EOC. Calculation results are presented in Table 3. When the highest fissile content composition was assumed, the effective multiplication factor was calculated to be the largest at 1.12785, and the difference of effective multiplication factor between fresh and spent nuclear fuel was 964 pcm with all three cases exceeding regulatory limit.

Table Ⅲ: Criticality effect of burnup for Problem Description

burnup stage	**BOC**	**MOC**	**EOC**
fuel composition	Fresh Fuel (12.25wt %)	Maximum Fissile Density	Spent Fuel
k-eff for transportaion when cask is filled with water	1.12001	1.12837	1.11037
Standard deviation (%)	0.029	0.021	0.021
△k from regulation limit (%)	17	18	16

3. All-Rod-In Transportation

As a way to lower the effective multiplication without changing the core design, All-Rod-In transportation case was evaluated. All control rods were inserted into the core and a 10cm thick boron plate was installed additionally inside of the cask internal wall. Even when the concentration of B-10 was enriched up to 40% to provide maximum absorption, effective multiplication factor was calculated to be 0.94670± 0.00016.

Consequently, transporting the LFR icebreaker core requires a special strategy to design a control rod assembly with a high control rod worth to lower the high effective multiplication factor or to design intensive neutron absorber in the Cask. However, the current core model is done for a preliminary design, the detailed design optimization should be carried out in the future.

3. Conclusions

Core designs have been performed to apply LFR with U-Zr fuel to a reactor for icebreaker. Because of high thermal conductivity of the metal nuclear fuel and the characteristics of fast reactor that does not require a moderator, core size can be reduced to be fit to transportation casks.

A feasibility of transportation of whole core with all fuels inside was checked in aspect of criticality safety. Many kinds of accidental scenarios were tested such as optimum moderation condition, higher breeding condition, etc.

In order to satisfy sub-criticality limit, all control rod should be inserted during transportation with additional absorber; 10cm thick 40% enriched boral plate. For the engineered condition with full absorber in, k-effective became lower than 0.95; up to 0.9467. In case of Pb-Bi cooled SMR, reactivity control can be done only by control rods without chemical shim and burnable poisons. Therefore more safety margin should be applied for criticality safety of reactor both under normal operation and accidental conditions. The results shown in this paper is calculated based on preliminary core design before detail optimization on fuel design and transportation strategies. therefore following job should be done later.

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