Analysis on Reactor Criticality Condition and Fuel Conversion Capability Based on Different Loaded Plutonium Composition in FBR Core

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Abstract. Reactor criticality condition and fuel conversion capability are depending on the fuel arrangement schemes, reactor core geometry and fuel burnup process as well as the effect of different fuel cycle and fuel composition. Criticality condition of reactor core and breeding ratio capability have been investigated in this present study based on fast breeder reactor (FBR) type for different loaded fuel compositions of plutonium in the fuel core regions. Loaded fuel of Plutonium compositions are based on spent nuclear fuel (SNF) of light water reactor (LWR) for different fuel burnup process and cooling time conditions of the reactors. Obtained results show that different initial fuels of plutonium gives a significant chance in criticality conditions and fuel conversion capability. Loaded plutonium based on higher burnup process gives a reduction value of criticality condition or less excess reactivity. It also obtains more fuel breeding ratio capability or more breeding gain. Some loaded plutonium based on longer cooling time of LWR gives less excess reactivity and in the same time, it gives higher breeding ratio capability of the reactors. More composition of even mass plutonium isotopes gives more absorption neutron which affects to decreasing criticality or less excess reactivity in the core. Similar condition that more absorption neutron by fertile material or even mass plutonium will produce more fissile material or odd mass plutonium isotopes to increase the breeding gain of the reactor.

1. Introduction

Recycling option of spent nuclear fuels option from discharged LWR fuels is one of the important issues to be pursued because of the potential to extend the sustainability of nuclear fuel such as recycling program of used uranium and plutonium, instead of once through fuel option. Other spent nuclear fuel material such as minor actinides or MAs can be utilized also for recycling nuclear fuel program in order to reduce spent nuclear fuel (SNF) composition and to increase the level of nuclear proliferation resistance. Fast reactor technology which uses fast neutron spectrum region, shows better fuel breeding capability and at the same time, it has a better level of reducing spent nuclear fuels by burning process. It also show better criticality condition as well as higher fuel breeding because of
high eta value of fissile materials at fast neutron energy region. Minor actinide (MA) material as transuranium material is also can be used to produce protected plutonium proliferation which can improve nuclear nonproliferation level [1-5]. Several recycling programs of SNF have been extensively conducted for long life core reactor program [6-7], increasing burning MA rate [8], and better transmutation TRU rate [9] and a program for recycling MA in light water reactor (LWR) type [10]. Reactor criticality condition and nuclear fuel breeding ratio are evaluated in the present study which is based on fast breeder reactor (FBR) type. Fuel loading are based on some different supply fuels which is mainly from different loaded plutonium composition in the fuel core regions.

2. Methods

Analysis on LWR fuel composition have been conducted by using depletion code of ORIGEN computer code [11] for different fuel burnup condition and cooling time process. Those LWR SNF compositions are used for initial loaded nuclear fuel of FBR. In term of FBR evaluations such as criticality condition, fuel composition and conversion ratio capability of the reactor have performed by using a coupling codes including SLAROM code, JOINT and CITATION codes. In this evaluation, nuclear data library was using JFS-3-J-3.2R for nuclear data analysis of investigated reactor systems which is based on the JENDL 3.2 [12-15]. JSFR (Japan Sodium Fast Reactor) design was used as the basis design for this evaluation [16].

2.1. Breeding Ratio

In this investigation, a parameter of nuclear fuel sustainability will be based on nuclear fuel breeding ratio which is based on some reaction rates of some fissile and fertile materials of nuclear fuels as shown in Eq. 1.

\[
BR = \frac{\sum_{i=1}^{n} \Sigma_{c,i}^{fertile}}{\sum_{i=1}^{n} \Sigma_{a,i}^{fissile}}
\]

(1)

\(\Sigma_{c,i}^{fertile}\) : Macroscopic capture cross-section of \(i\) isotope for fertile materials

\(\Sigma_{a,i}^{fissile}\) : Macroscopic absorption cross-section of \(i\) isotope for fissile materials

As mention in Eq. 1, ratio of breeding is based on a ratio between capture cross-section of fertile materials and absorption cross-section of fissile materials. Main fertile material are U-238, Pu-240 and Pu-238 and fissile materials are U-235, Pu-239 and Pu-241. Some different plutonium compositions in the core as initial loaded fuel will give a signify contribution to reactor performances especially for breeding ratio capability and criticality condition during reactor operation.

3. Results and Discussion

Obtained results of uranium and plutonium based on SNF of LWR are shown in Table 1 and 2 for different fuel burnup process and cooling time. Isotopic vector composition has some differences depending on burnup and cooling time. Some plutonium isotopes are increasing and some others are reducing for longer cooling time due to the half-life of the plutonium isotopes and conversion process from nuclide to another nuclide. Higher burnup affects to increases all isotopic plutonium composition except for Pu-239 which is reducing for higher burnup. Reducing Pu-239 is estimated from fission reaction from Pu-239 for reactor operation.
Table 1 Plutonium composition of spent nuclear fuel composition LWR for different cooling time.

| Plutonium | Cooling Time [Years] |
|-----------|----------------------|
|           | 5.0  | 30.0 |
| Pu-238    | 3.00 | 2.70 |
| Pu-239    | 52.62| 57.63|
| Pu-240    | 24.50| 27.23|
| Pu-241    | 12.20| 4.01 |
| Pu-242    | 7.69 | 8.42 |

Table 2 Plutonium composition of spent nuclear fuel composition LWR for different burnups.

| Plutonium | Cooling Time 30 [Years] |
|-----------|-------------------------|
|           | 33  | 50.0 |
| Pu-238    | 1.464| 2.704|
| Pu-239    | 63.618| 57.632|
| Pu-240    | 25.757| 27.227|
| Pu-241    | 3.557| 4.014|
| Pu-242    | 5.605| 8.423|

3.1 Criticality Operation Condition
Reactor operation is directly related to a criticality conditions of the reactor which is based on the fission reaction that occurs during reactor operation. Obtained some criticality conditions are shown in Figures 1 and 2 for different fuel loading in the core region. As mentioned before it is estimated some different fuel composition will affect to the reactor criticality condition especially from the initial fuel loading. It shows some different criticality conditions of FBR during reactor operation up to equilibrium reactor condition for different composition of loading fuel based on different cooling time process and fuel burnup. Initial criticality condition is estimated higher than equilibrium fuel composition because of more fission occur for initial fuel condition and it becomes less when fissionable materials are decreasing as well as production of some nuclide which absorb neutron. In term of different cooling time, it shows that longer cooling time of loaded SNF LWR in the FBR gives a reduction value of criticality condition at the beginning of cycle (BOC) and equilibrium condition. In initial reactor condition, less criticality means less reactor reactivity that stability of neutron population can be reduced.
Figure 1. Criticality condition of FBR core based on different cooling time of loaded SNF LWR
BOC: Beginning of cycle
Equi: Equilibrium cycle

Figure 2. Criticality condition based on different burnup process of loaded SNF

It is expected to have less criticality condition for higher burnup as shown in Figure 2 that more burnup value obtains less criticality condition for both BOC and equilibrium condition. Longer burnup is estimated to have less fissile material such as fissile plutonium for maintaining reactor operation. Based on the results, more cooling time process is used and higher level of fuel burnup is increased will obtain a better safety condition in term of less excess reactivity or less excess neutron production during reactor operation, especially in initial reactor operation.
3.2. Fuel Breeding Ratio

Fuel breeding ratio is evaluated during reactor operation up to equilibrium condition which are shown in Figures 3 and 4 as fuel breeding profile based on different loaded fuel types of SNF LWR into the FBR cycle. Longer reactor operation affect to increases fuel breeding ratio value for both cooling time processes and it shows more significant increasing fuel breeding value for for initial breeding ratio of FBR than at equilibrium condition. Fuel breeding ratio of the reactor is increasing with increasing cooling time and it shows a slightly increase for equilibrium reactor condition. Some loaded actinide SNF composition based on higher burnup obtain better breeding ratio of FBR cycle for all reactor operation such as beginning of operation up to equilibrium condition as shown in Figure 4. Better level of fuel breeding ratio is estimated from the increase of fuel conversion capability of fertile materials into fissile materials. In relation to criticality condition, less criticality obtains better fuel breeding. This condition can be expected from capturing more neutron will reduce excess reactivity which corresponding to reactor criticality. At the same time, capturing neutron by actinide was used to convert some fertile materials into fissile materials during reactor operation.
4. Conclusions
Reactor criticality condition and nuclear fuel breeding ratio have been investigated based on fast breeder reactor (FBR) type. Initial fuel loading are based on some different supply fuels of spent nuclear fuel of LWR which is mainly from different loaded plutonium composition in the fuel core regions. Some plutonium isotopes are increasing and some others are reducing for longer cooling time due to the half-life of the plutonium isotopes and conversion process from nuclide to another nuclide. Higher burnup affects to increases all isotopic plutonium composition except for Pu-239 which is reducing for higher burnup. Initial criticality condition is estimated higher than equilibrium fuel composition. Longer cooling time process and higher level of fuel burnup give a better safety condition in term of less excess reactivity or less excess neutron production during reactor operation, especially in initial reactor operation.

Longer reactor operation affect to increases fuel breeding ratio and it increases with increasing cooling time. Loaded actinide composition based on higher burnup of SNF LWR obtain better breeding ratio of FBR cycle for all reactor operation. Higher fuel breeding ratio is estimated from the increase of fuel conversion capability of fertile materials into fissile materials. In relation to criticality condition, less criticality obtains better fuel breeding. This condition can be expected from capturing more neutron will reduce excess reactivity which corresponding to reactor criticality. At the same time, capturing neutron by actinide was used to convert some fertile materials into fissile materials during reactor operation.

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