Current Status of the Development Project on Erbia Credit Super High Burnup Fuel

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Current Status of the Development Project on Erbia Credit Super High Burnup Fuel

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Abstract. In order to reduce the number of spent fuel assemblies and to improve fuel cycle economics, the development project on 'Erbia credit Super High-Burnup' (=Er-SHB) fuel with above 5 wt% uranium enrichment is in progress. The program covers wide aspect of the development of LWR fuel, in which low content of Erbia is fully distributed. In this paper, (1)outline of the concept of Er-SHB fuel, (2) measurement and analyses results of critical assembly experiment with fully Erbia loaded core, (3) 'Erbia COntent for Sub-criticality judgment (=ECOS) diagram' defined by a series of criticality safety analyses for typical geometries, are presented.

1. Introduction

An extended longer cycle operation and higher discharge burnup are believed to be effective to realize better economy of generation cost. However, it is known that as the cycle length becomes longer, as the batch averaged discharge burnup becomes lower. This means cycle length and discharge burnup is conflicting each other then there should exist the optimal point of generation cost in some condition. Actually in some papers focusing on this complex proposition, it is mentioned that the optimal discharge burnup will be around 60 to 70 GW•d/t and its corresponding enrichment should be above 5 wt% in PWR [1–2].

However, the value of '5 wt%' is a current criticality safety restriction in front-end of fuel cycle stream, such as fabrication, transportation, storage and so on. Therefore, straightforward approach of higher enrichment fuel requires major modifications and re-licensing of these facilities, then that considerable cost may spoil the economic advantage of the higher enrichment fuels. In a past session of American Nuclear Society (ANS) in 1998, sponsored by Nuclear Criticality Safety Division (NCSD), this challenge were named as "the 5wt% Barrier: Nuclear Criticality Safety in the Production of Extended-Burnup Fuel" [3–4].

The components of "the 5 wt% enrichment Barrier" can be summarized as follows;

- Lack of critical experiments at the range of 5 to 10 wt% enrichment, which makes difficult to validate a criticality safety analysis code in licensing process.
- The impact on the plant safety of the fact that a criticality accident can occur above 5 wt%. In the light of this fact, the Japanese Authority's guideline requests that the venders should address the detection equipments and the termination measures against a criticality accident when they use above 5 wt% UO_2 powder [5].
- The impact of reduced subcritical limits, which induces a reduction of the amount of treated UO_2 fuel. This means the efficiency, such as transport, fabrication, storage and so on, should be decreased as well.

To solve these issues, the development program on Erbia credit Super High Burnup (=Er-SHB) Fuel has been launched by the authors since 2005[6– 9]. The detail of Er-SHB fuel is described in later

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section, but its basic concept represents adding low content (>0.2 wt%) of Erbia in all UO_2 powder, so that a reactivity of high enrichment (>5 wt%) fuel should be suppressed under that of current fuel assemblies, i.e. below 5 wt% enrichment. Since Erbia is mixed into UO_2 powder at the time after a re-conversion process, the advantage of negative reactivity credit of Erbia can be taken in the most criticality safety issues appearing after the re-conversion process.

Although Erbia is one of the major burnable absorber used in LWRs and has rich experience, the concept of Er-SHB fuel is completely different from the conventional Erbia fuel. Currently, Erbia is used to control in-core power distribution and to suppress excess reactivity, and loaded in some portion of fuel rods in an assembly. Contrary to this on the Er-SHB fuels, Erbia is added in all the fuel rods to meet the criticality safety requirements.

The development program for the Er-SHB fuel covers wide aspect of the development of fully Erbia distributed fuel, as follows;

1) Critical experiments of Erbia core at the range of ^{235}U enrichment is 5 to 10 wt%
2) Development of an uncertainty reduction technique for neutronics parameters
3) Criticality safety analysis using Erbia credit
4) Fabrication test and physicochemical properties measurement of Erbia-bearing fuel pellet
5) Core design using the Er-SHB fuel assemblies
6) Applicability of burnup credit for the Er-SHB fuels
7) Effect on the back-end stream such as disposal of high-level radioactive waste (HLW), etc.

The five organizations who are involved in this development project are NFI, Osaka University, Nagoya University, Kyoto University and NEL. NFI is taking a role of project manager. This project is subsidized by the Innovative and Viable Nuclear Energy Technology (IVNET) development framework of Ministry of Economy, Trade and Industry (METI). Since FY2008, some part of this project is merged into Japanese National Project named 'the Development Project on Next Generation Light Water Reactor' that is also supported by METI. The original part of the project, which is described in this paper, is still conducted by above five organizations.

In this paper, (1) outline of the concept of Er-SHB fuel, (2) measurement and analyses results of critical experiment with fully Erbia loaded core, (3) '**E**rbia **CO**ntent for **S**ub-criticality judgment (=ECOS) diagram' defined by a series of criticality safety analyses for typical geometries, are presented.

2. Concept of Er-SHB fuel

Criticality safety is one of the major concerns of an extended high burnup fuel whose ^{235}U enrichment is above 5 wt%. Currently, the limitation of 5 wt% enrichment is used throughout the front-end stream of LWR fuels. In the Er-SHB fuel, Erbia is mixed into UO_2 powder just after the re-conversion process. Since Erbia is a neutron absorber, reactivity of UO_2 can be suppressed. By properly adjusting the content of Erbia, reactivity of Erbia-mixture fuel can be lower than that of current fuels whose enrichment is 5 wt%. Such Erbia-mixed fuel can be handled in similar way with the current fuels. In other words, by adding Erbia as burnable absorber, higher enrichment fuel (>5 wt%) can be handled by conventional equipments in the front-end stream. Such simplification of fabrication process will contribute to reduce fuel costs. There are another neutron absorbers commonly used in LWR than Erbia, e.g., boron and gadolinia, those are more familiar because of rich experiences in LWR fuels. However, these materials are difficult to be used as the present concept because of following reasons;

- Absorption cross section of gadolinia is much larger than that of Erbia, as shown in Figure 1. Therefore, in the case where gadolinia is mixed into all the fuels as burnable absorber, reactivity hold-down by gadolinia at BOL becomes too large as shown in Figure 2. The cores loaded with such fuels would be difficult to control the core reactivity. (Remember that the poison is mixed into all UO_2 powder in the fuel)

- Furthermore, gadolinia burns out too rapidly due to its 'blackness' hence reactivity change during burnup becomes extremely quick and large. Such rapid variation of reactivity makes in-core power peaking to be too steep.

- On the contrary, since absorption cross section of Erbia is smaller than that of Gadolinia, initial reactivity of Erbia-bearing fuel becomes appropriate. The moderate burnup behavior gives appropriate design window for reload core analyses (Figure2).

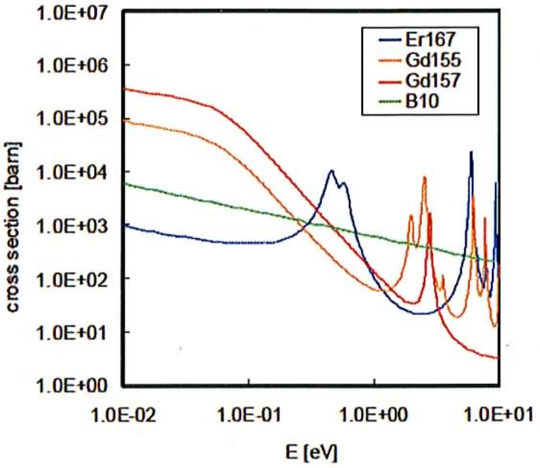


FIG. 1. Cross sections of various burnable absorbers.

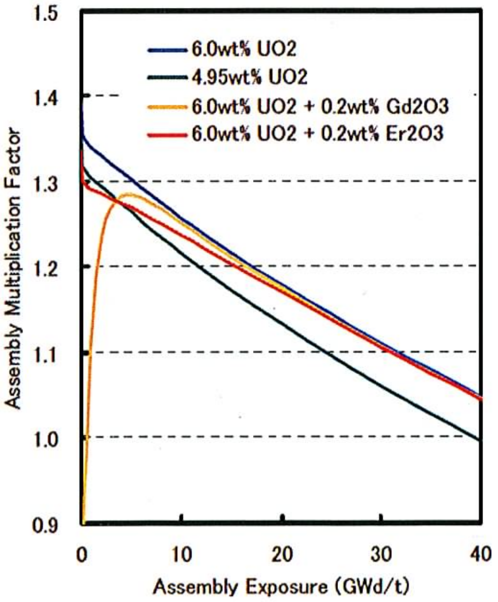


FIG. 2. Multiplication factor versus burnup for various PWR fuels.

3. Critical experiments in KUCA

Erbia has rich experience as burnable absorber in LWR. From this point of view, neutronics property can be adequately predicted in LWR core conFigurations. However, the major objective of adding Erbia into all UO_2 powder is countermeasure of criticality safety issues. In the criticality safety analysis, many conFigurations with various moderator conditions should be analyzed. Furthermore, Erbia will be used with higher enrichment (>5 wt%) fuels, which is not commonly used in LWRs. Therefore, new critical experiments that can provide appropriate verification data are highly desirable.

In the conventional critical facility with pin-types, Er bearing fuel pellets should be prepared in advance to critical experiments. Therefore, content of Erbia is fixed to specific values and difficult to change. Furthermore, in order to change neutron spectrum, i.e. moderation ratio ($H/^{235}U$), different lattice pitch, insertion of water displacement micro-rods and/or different moderator materials should be used. Since such experiments would require considerable efforts, systematic investigation on Erbia content and neutron spectrum variation would be restricted.

These experimental data are so valuable to validate neutronic analysis codes, those are used for criticality safety analysis of Er-SHB fuel.

3.1 General description on KUCA

Kyoto University Critical Assembly (KUCA) has a solid moderated plate type fuel cores. A schematic view of the core is shown in Figure 3.

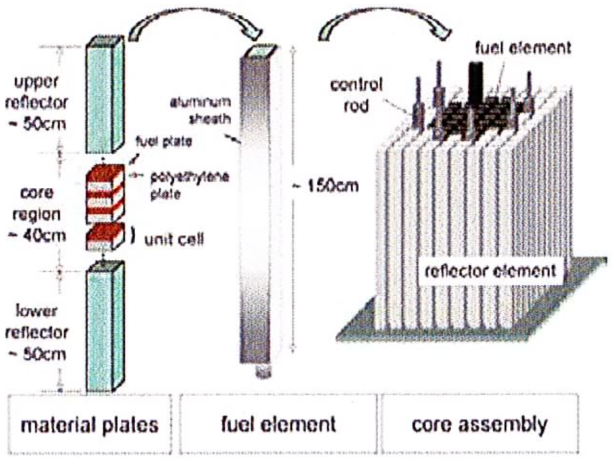


FIG. 3. A schematic view of solid moderated core.

As the fuel plate in KUCA, 1/16 inch (1.6 mm) thickness high enriched (93 wt%) U-Al alloy (EU) and 1mm thickness natural uranium metal (NU) are used. Both of them have 2 inches (50.8 mm) square shape in radial direction. For moderator material, polyethylene and graphite plate of various thicknesses are used. Adjusting a combination of fuel and moderator plates, various fuel enrichments and moderation ratio can be simulated. Adding those plates, in order to perform critical experiments with massive loading of Erbia, one thousand pieces of thin Erbia coated graphite plates are prepared. Figure 4 shows the Erbia-coated graphite plate which consists of graphite plate (50.8 mm×50.8 mm×1.5 mm) with 0.2 mm depth engraved surface where Erbia is coated with 30 micro meter thickness. The amount of Erbia per plate is approximately 0.3 g. In order to perform critical experiments with massive loading of Erbia, one thousand pieces of the Erbia coated graphite plates are prepared.

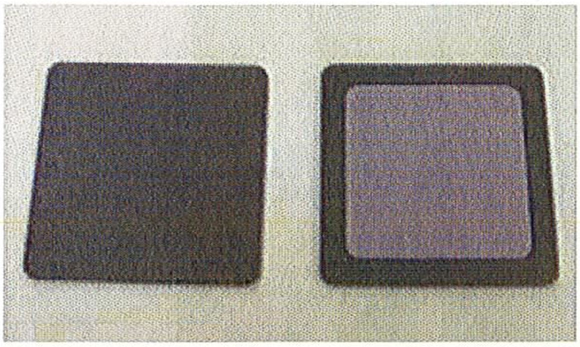


FIG. 4. Erbia-coated graphite plate.

The first fully Erbia-loaded core (refer as core-1 in this paper) has achieved critical in December 2006. Following the first experiment, another two criticality experiments have conducted from December 2007 to January 2008. Average enrichment of core-1 is 5.4 wt% and average content of Erbia is 0.3 wt%. Average enrichment of another two criticality experiments in KUCA (refer to them as core-2 and core-3) are 5.4 wt% and 9.6 wt%, and average content of Erbia are 0.3 wt% and 0.6 wt%, respectively. Following those experiments, the forth core (refer to this core as core-4), had achieved critical in December 2008. This core is aimed to contain rather high content of Erbia into whole core. The realized Erbia content is 1.12 wt% and an average enrichment of core-4 is 9.6 wt%, same as core-3. The core properties of above four cores are summarized in Table 1.

Cell structures of each core and core conFigurations of the fuel elements are shown in Figure 5 and Figure 6 respectively. Neutron spectrum of those cores, which is obtained by cell calculation using SRAC code [10] are shown in Figure 7.

As described in Table 1, the series of these experiments appropriately cover the features of Er-SHB fuel such as;

- At the range of uranium enrichment is above 5 wt% from 5 to 10 wt%
- Erbia is fully loaded into the whole core of which content is rather low compare to conventional Erbia fuel (0.3 to 1.12 wt%)
- A moderator ratio varies from 48 to 274, which represents various neutron spectra from hard to soft.

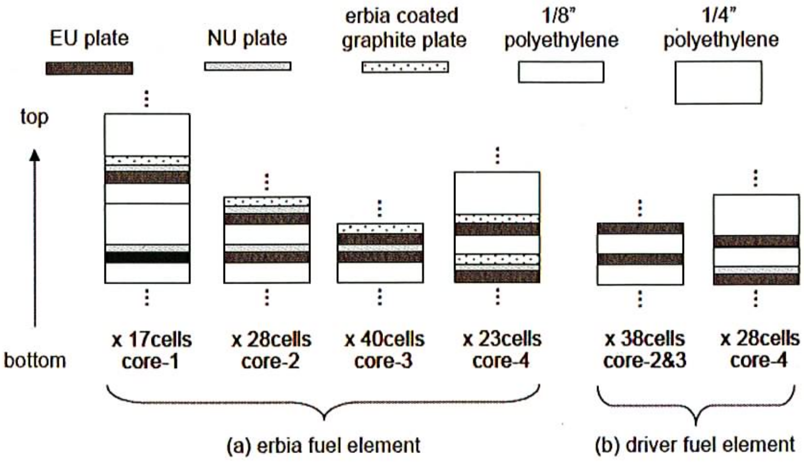
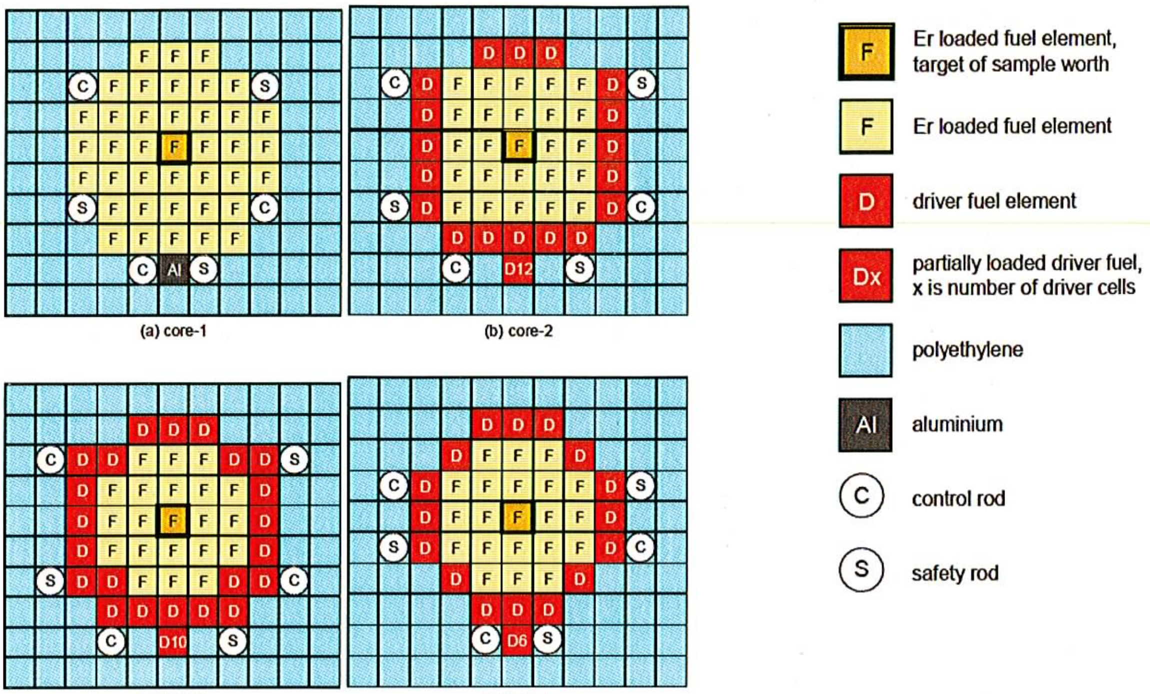


FIG. 5. Cell structure of fuel element.



(a) core-1
(b) core-2
(c) core-3
(d) core-4

FIG. 6. Core configuration of fuel elements.

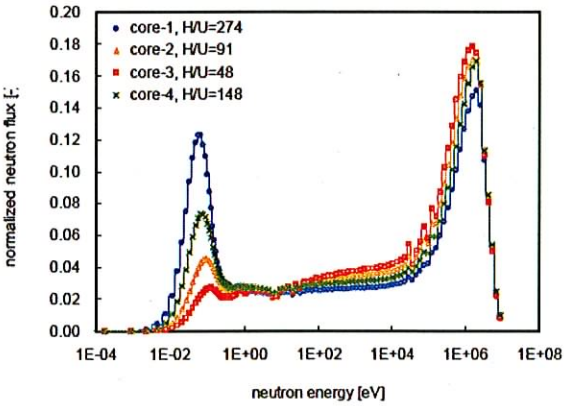


FIG. 7. Neutron spectrum of each core.

TABLE 1. COMPARISON OF CORE PARAMETERS

Case	Average enrichment	Er content*1	$H/^{235}U$	Outline
Core–1	5.4 wt%	0.3 wt%	274	Homogeneously Er loaded core Very soft spectrum
Core–2	5.4 wt%	0.3 wt%	91	Zone type core with driver Simulate PWR spectrum
Core–3	9.6 wt%	0.6 wt%	48	Zone type core with driver Harder spectrum
Core–4	9.6 wt%	1.12 wt%	148	Zone type core with driver Higher Er content

**1: Erbia / U-total.*

3.2 Experiment

3.2.1 Criticality

For each core, approach to criticality has been performed based on inverse multiplication method. The inverse multiplication curves versus the number of loaded fuel elements were calculated prior to the experiments using the continuous energy Monte Carlo code MVP [11]. The pre-calculated curves shows in excellent agreement with the actual measurements. The detailed reactivity is adjusted by control rod. After achieving criticality, all control rods are withdrawn then the excess reactivity of each core is measured by using the period method. In the period method, the effective delayed neutron fraction and prompt neutron life time have been evaluated by the deterministic code SRAC.

3.2.2 Erbia sample worth

Erbia sample worth is defined as reactivity induced by replacing a Erbia plate with a graphite plate. The measurement of Erbia sample worths has been carried out in this series of experiments. This measurement is aimed at providing the database for confirmation of erbium cross section and improvement of prediction uncertainties of Er-SHB PWR core characteristics using the generalized bias factor method. In the experiment, the Erbia-coated graphite plates loaded in the central fuel element (See Figure 6) are replaced by the graphite plates one by one. This replacement has been made axially from the middle height of the fuel element then expanding to top and bottom direction symmetrically; the number of Erbia-coated graphite plates is increased in several steps until all the plates in the central fuel element were replaced. The Erbia sample worth was measured as reactivity difference caused by the replacement. The reproductivity of the Erbia sample worth measurement, defined as the relative standard deviation for several measurements, is estimated to be less than 3% for most cases.

3.3 Analysis

3.3.1 Criticality

Analyses of criticality have been performed by using the energy Monte Carlo code MVP. The core geometries and material compositions were treated rigorously as file as possible. The nuclear data libraries used in the MVP analyses are JENDL-3.3, ENDF/B-VI.8, JEFF-3.0, ENDF/B-VII.0 and JEFF-3.1. Neutron multiplication factor, k_{eff}, for each core is evaluated from statistical results of total 50 000 000 (= 50 millions) histories, i.e., 50 000 histories/ batch × (1 050 total batches – 50 skipped batches).

Figure 8 shows the comparison of C/E values of k_{eff} for different nuclear data libraries. Here, the error bars represent the 3σ statistical errors of Monte Carlo calculations. For all cases, the C/E values of k_{eff} are predicted within 0.998– 1.004 and the maximum differences among libraries are approximately 0.003, thus the prediction accuracy of criticality for Erbia loaded core is validated. As shown in Figure 8, there are some notable trends among the libraries, e.g., JEFF-3.1 and especially ENDF/B-VII.0 tend to overestimate k_{eff}, and contrary ENDF/B-VI.8 tends to underestimate compared with another libraries. It is supposed that the significant differences between ENDF/B-VI.8 and ENDF/B-VII.0 results are mainly caused from difference in ^{238}U capture cross section.

3.3.2 Erbia sample worth

In order for analyses of Erbia sample worth, firstly the Monte Carlo code MVP was intended to use. Shown in Figure 7 as an example, the results of MVP agree with experiment within statistical errors of Monte Carlo calculations. However, because the absolute value of the Erbia sample worth is too small, the statistical errors are comparable large to quantitatively investigate the differences among nuclear data libraries.

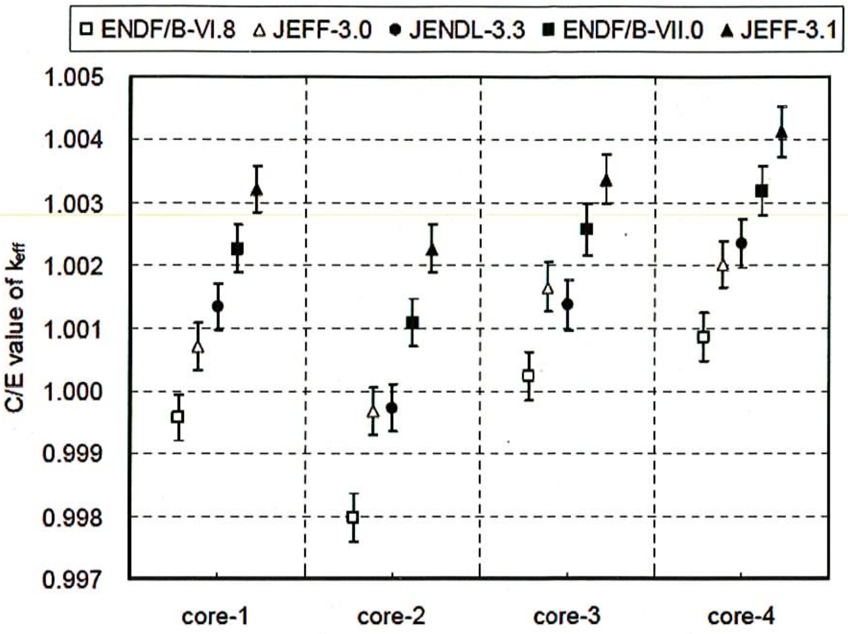


FIG. 8. Numerical results of k_{eff} by Monte Carlo code MVP.

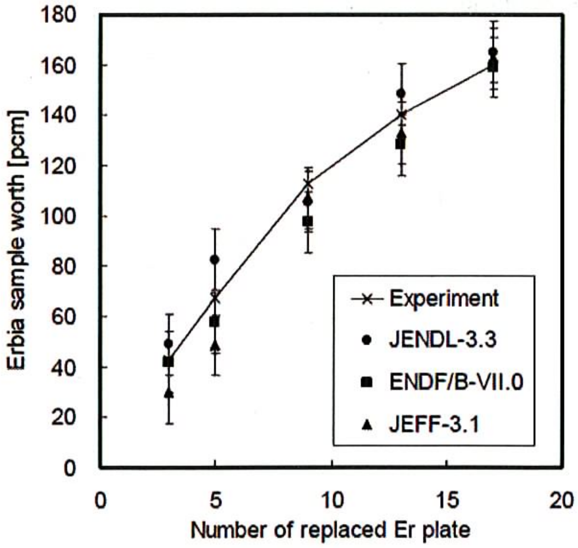
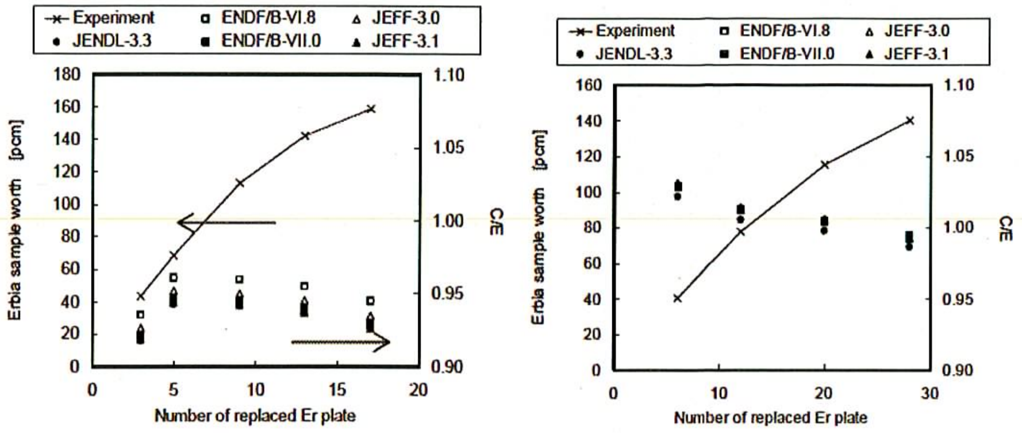


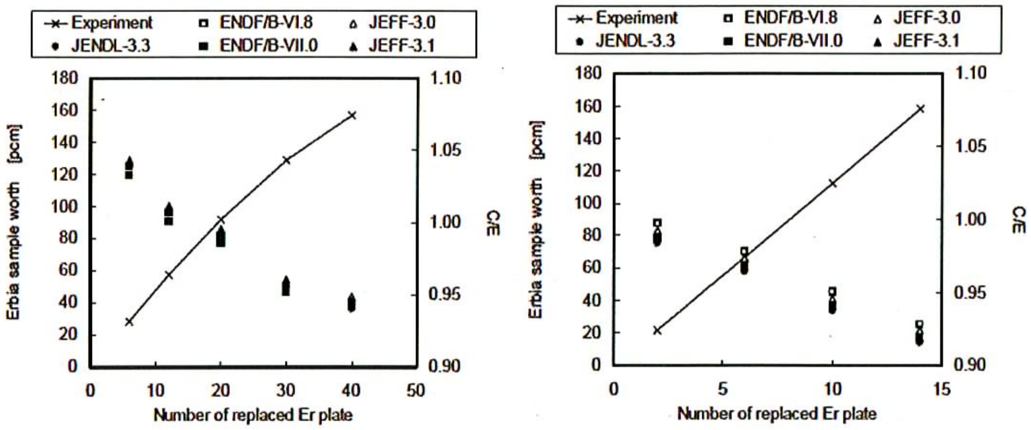
FIG. 9. Numerical results of Erbia sample worth by Monte Carlo code MVP (core-1).

Therefore, analyses of Erbia sample worth have been performed by using the deterministic code SRAC. The numerical results are evaluated by perturbation theory using 3-D XYZ diffusion calculation with 30 energy groups. Same as the criticality analyses, several nuclear data libraries were used for analyses. Numerical results of Erbia sample worth by 3-D XYZ diffusion calculation are summarized in Figure 10. Taking into account that the experimental accuracy for Erbia sample worth, which is approximately 3%, it could be concluded that the agreement between calculation and measurement of Erbia sample worths are reasonable. However, it is noted that there are downward trends of the C/E values for all core conFiguration as the number of replaced Er plate are increased. There seems to be some considerations for the treatment of heterogeneous effects in the fuel elements should needed, then further study will be performed to re-evaluate the C/E values.



(a) core-1

(b) core-2



(c) core-3

(d) core-4

FIG. 10. Numerical results of Erbia sample worth by 3-D XYZ diffusion calculation.

4. Criticality safety analysis

In this section, from the viewpoint of criticality safety for fabrication facilities, the sufficient of Erbia content for Er-SHB fuel is evaluated. The contents of Erbia is determined in order to secure the same criticality safety level as the conventional fuels whose enrichment is 5 wt% or lower.

Three kinds of condition are evaluated. The first one is simple geometric shapes, the second one is a large sphere with moisture control and the third one is fuel assemblies in storage rack.

4.1 Calculation method and validation data

In criticality safety analysis for fabrication plant, KENO V.a and 44-group library equipped in SCALE5 [12] code system are used for calculate neutron multiplication factor (k_{eff}) and criticality safety data, because SCALE5 has a lot of experiences for such analyses purpose.

As a first step, the validity of our analysis scheme is checked by comparison with well-known results, whose enrichment is 5 wt% or lower and whose geometry is simple shapes such as sphere, cylinder and slab without neutron absorber. As a typical case, the result of the sphere UO_2 volume on corresponding to the lower limit of k_{eff} is shown in Figure 11. The calculated results for simple shapes agree with the reference [13] as shown in Figure 11. From these results, it is confirmed the validity of our analysis code and scheme.

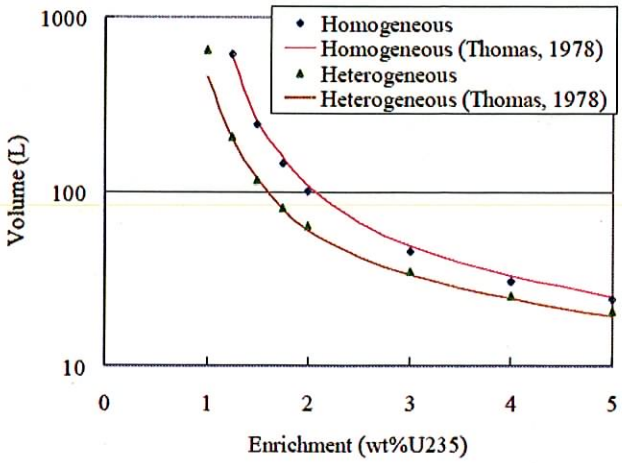


FIG. 11. Volume of UO_2 sphere of the lower limit.

Because of a shortage of benchmark data of criticality experiment with Erbia, criticality experiments are conducted in KUCA, as described in section 3. The criticality analyses for KUCA are performed by using a continuous energy Monte Carlo code MVP because in SCALE library, only two isotopes of Erbia (^{166}Er and ^{167}Er), which have large absorption cross section, are considered. However, considering the consistency and experience with current criticality safety analysis for fuel facilities, the SCALE system is used in this section.

In comparison with the measured data and the calculation results by MVP, k_{eff} bias with Erbia for each library is consistent with that of without Erbia. Because the negative reactivity caused by Erbia is mainly by ^{166}Er and ^{167}Er, the impact of neglecting the other isotopes such as ^{168}Er or ^{170}Er are also negligible for k_{eff} evaluation. Therefore, it is expected the criticality analysis on Erbia by SCALE will comparable to that by MVP. In order to assure this, series of criticality analyses for KUCA experiments by SCALE are undergoing, now.

In the calculations of k_{eff} for enrichment of 5 wt% or lower without Erbia, criticality parameters are optimized so that the reactivity becomes maximal under criticality safety control of each geometry. As a same manner, in evaluation of Erbia content for enrichment higher than 5 wt%, criticality parameters are similarly optimized under the same criticality safety control, and the Erbia content is determined so that the k_{eff} is equivalent to the ones for enrichment of 5 wt% without Erbia. Therefore, by adding the obtained Erbia content, criticality safety is secured in the equivalent criticality safety control.

4.2 Calculated geometories

4.2.1 Simple shapes

Simple shapes such as sphere, cylinder and slab, for sub-criticality condition are very important data, that are often used for the purpose of the criticality safety control. In this section, it is considered the simple geometric shapes that are surrounded by water reflector. Each homogeneous mixture of UO_2 and water, and heterogeneous UO_2 and water are respectively considered as fuel material. In this paper, the result of sphere is representatively described, because others show a almost similar behaviour.

The dimension of geometry (radius, thickness, and so on) is a criticality safety control factor, and determined so that the k_{eff} equal to the lower limit of subcriticality (= 0.98). Other parameters concerning neutron moderation are optimized. In these manners, 1) the ratio of UO_2 to water in the homogeneous case, and 2) the radius and the pitch of pellet in the heterogeneous case, are changed in a physically possible range. As a result of homogeneous sphere, the radius of 5 wt% enrichment is 18 cm.

4.2.2 *Large sphere with moisture control*

By restricting the moisture condition as a criticality safety control factor, the amount of fuel in a facility has increased in comparison with simple shapes. Here, we consider a homogeneous sphere made of UO_2 and water surrounded with water reflector. The range of parameters is determined to cover the practical condition as follows.

- Moisture: H/U (number density ratio) ≤ 1
- Powder density: $UO_2 \leq 3.5$ g/cm^3
- Volume of sphere: 800 L (Radius: ~ 58 cm)

The k_{eff} of this large sphere of 5 wt% enrichment is calculated to be 0.874. Therefore, the Erbia content for the large sphere whose enrichment is above 5 wt% is determined so that the k_{eff} becomes 0.874, while changing the parameters of H/U and powder density in the above mentioned ranges. The results will be shown in the section 4.3.

4.2.3 *Fuel assemblies in storage rack*

In order to reduce the neutron interaction between each assemblies, structural material with neutron absorber (here, borated SUS) is constructed around the fuel assembly. A practical fuel assembly storage rack could be variously designed in order to satisfy the limitation of k_{eff} which depends on the structural material, dimensions (ex.: rack pitch, thickness, distance between assembly and absorber), placement, type of fuel assembly, number of array, and so on.

Here, the calculated geometry of the fuel assembly storage rack is modelled to be simplified as shown in Figure 12. The fuel assembly is conventional 17×17 type PWR fuel assembly, but its enrichment is set to 5 wt% (the current upper limit) and pellet density is set to 100%TD. The structure of fuel assembly except the fuel rod (grid, nozzle, and so on) is not considered. The fuel assembly storage rack is an infinite array in horizontal direction, and water reflector is assumed at the top and bottom in vertical direction. In order to consider the optimal neutron moderation in the calculations, the storage rack is assumed fully flooded with water and the water density is changed uniformly from 0% to 100%.

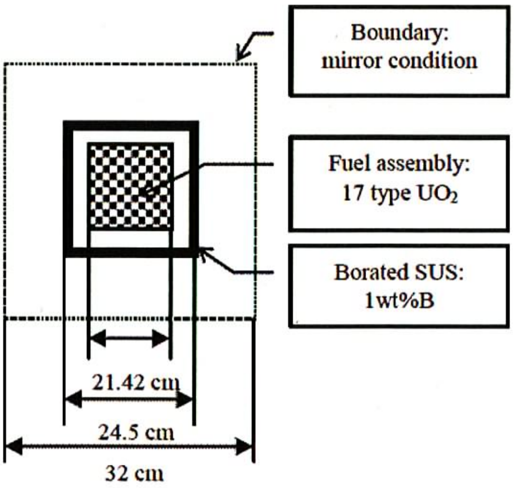


FIG. 12. Horizontal geometry of fuel assembly storage rack.

The k_{eff} of this fuel assembly storage rack of 5 wt% enrichment is calculated to be 0.937. Therefore, the Erbia content for the fuel assembly storage rack whose enrichment is above 5 wt% is determined so that the k_{eff} becomes 0.937, while changing water density. Other parameters except enrichment and Erbia content (geometry, structural materials, and so on) are fixed.

4.3 Results of Erbia content

4.3.1 Simple shapes

The result of Erbia content for homogeneous sphere is representatively shown in Table 2. As shown in Table 2, the Erbia content of simple shapes increases linearly with increase of enrichment.

Homogeneous and heterogeneous simple shapes (sphere, cylinder and slab) are summarized as follows.

- Erbia contents of the homogenous cases are greater than that of heterogeneous cases, where the neutron spectra of the homogeneous cases are consistently slightly harder than that of the heterogeneous cases.
- Erbia contents are almost the same among the homogeneous simple shapes.
- The ratio of $H/^{235}U$ for the optimal moderation condition increase linearly with increase of enrichment of ^{235}U.

Therefore, the simplification to use the result of the homogeneous sphere for all simple shapes is conservative in the viewpoint of criticality safety.

Table 2. Calculated result for homogeneous sphere

Enrichment (wt%)	Erbia content (wt%)	Powder density (g/cm^3)	$H/^{235}U$
5	0.00	2.22	118
6	0.28	1.69	150
7	0.58	1.64	175
8	0.89	1.47	204
9	1.19	1.32	233
10	1.15	1.16	263

4.3.2 Large sphere with moisture control

As the result of Erbia content for large sphere with moisture control, calculated result of k_{eff} for enrichment of 5 wt% and powder density in the practical parameter ranges is shown in Figure 13, at first. As shown in Figure 13, k_{eff} of this geometry increases monotonously with increase of H/U.

In cases with enrichment of above 5 wt%, k_{eff} increases with change of the parameters similarly. The calculated result of k_{eff} for enrichment of above 5 wt% in case of powder density of 3.5 g/cm^3 without Erbia is shown in Figure 14. The Erbia content to secure the equivalent criticality for enrichment of 5 wt% is shown in Figure 15. The Erbia content shows similar behaviour of k_{eff} and it becomes maximal at the maximal points in the parameter ranges.

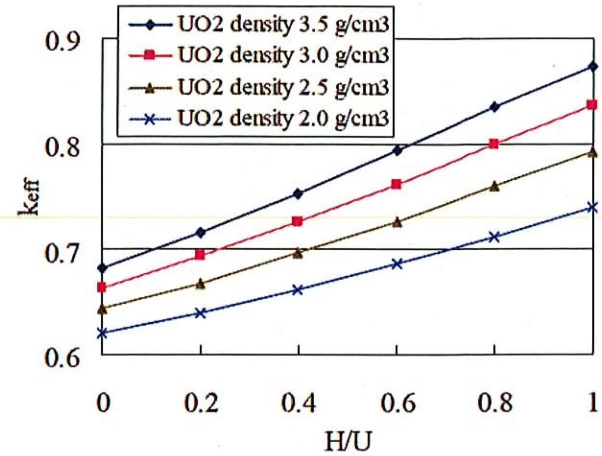


FIG. 13. Calculated results of k_{eff} for the large sphere with moisture control (enrichment 5 wt%).

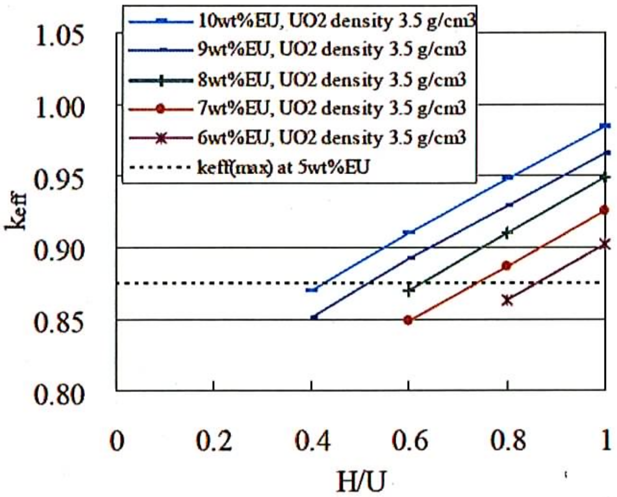


FIG. 14. Calculated results of k_{eff} for the large sphere with moisture control (enrichment higher than 5 wt%).

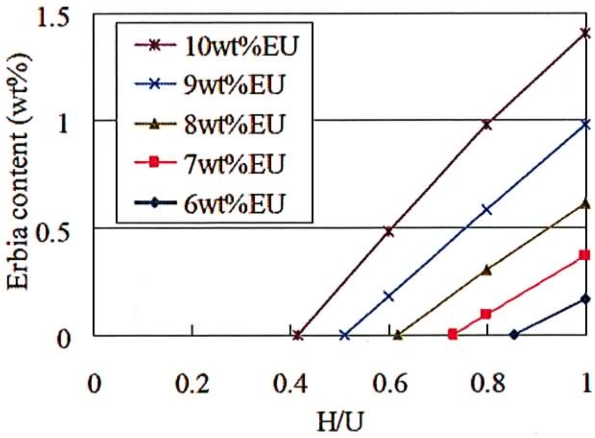


FIG. 15. Calculated results of Erbia content for the large sphere with moisture control.

4.3.3 *Fuel assemblies in storage rack*

The results of fuel assemblies in storage rack, whose enrichment is from 5 wt% to 10 wt% and without Erbia, is shown in Figure 16. Seeing in Figure 16, there is a hump of k_{eff} in the condition of low water density. In Table 3, the maximum value of k_{eff} and its water density, and k_{eff} at the fully flooded condition are shown. As shown in Figure 16 and Table 3, the point of water density that gives the maximum of k_{eff} jumps from 100% to 12% with the increase of enrichment from 5 wt% to 6 wt%, and it decreases slightly with increase of enrichment from 6 wt% to 10 wt%. Namely, the increasing change of k_{eff} at the lower water density is greater than that at the fully flooded condition.

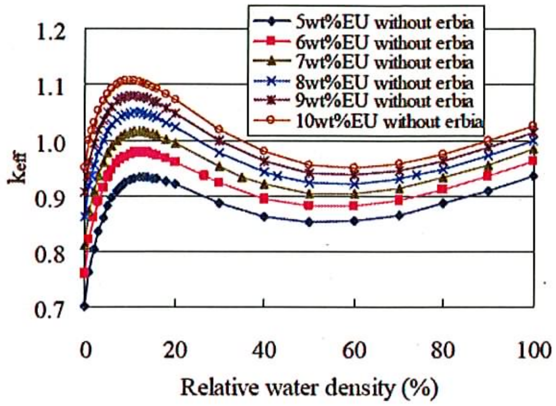


FIG. 16. Calculated results of k_{eff} for the fuel assembly storage rack without Erbia.

TABLE 3. CALCULATED RESULTS FOR THE FUEL ASSEMBLY STORAGE RACK WITHOUT ERBIA

Enrichment (wt%)	5	6	7	8	9	10
Maximal k_{eff}	0.937	0.979	1.017	1.051	1.080	1.108
Water (%)	100	12	12	11	11	10
k_{eff} at 100%	0.937	0.964	0.985	1.001	1.015	1.026

The hump of k_{eff} at low water density is observed in some case of repeated geometry where the neutron interaction between the units becomes large in the hard spectral condition. Figure 16 indicates that the maximal k_{eff} for above 5 wt% enrichment might appear at low water density, even in the case that a fuel assembly storage rack is designed so that the maximal k_{eff} for 5 wt% enrichment appears at the fully flooded condition.

The Erbia content of the fuel assembly storage rack to secure the equivalent criticality for enrichment of 5 wt% is shown in Figure 17.

As shown in Figure 17, the Erbia content of the fuel assemblies in storage rack also has a hump at a low water density. However, the point of water density that gives the maximum value of Erbia content is less than that of k_{eff} and the peak of the Erbia content is very steep. It is important to note that the reactivity worth of Er at low water density becomes small. It is found that the small reactivity of Er in the hard spectral condition makes its content very high in order to retain the large k_{eff} of above 5 wt% enrichment fuel at low water density.

Beware of the large amount of Erbia content at the low water density that induces the more neutron interaction, when the Erbia credit is introduced into a facility with repeated geometry.

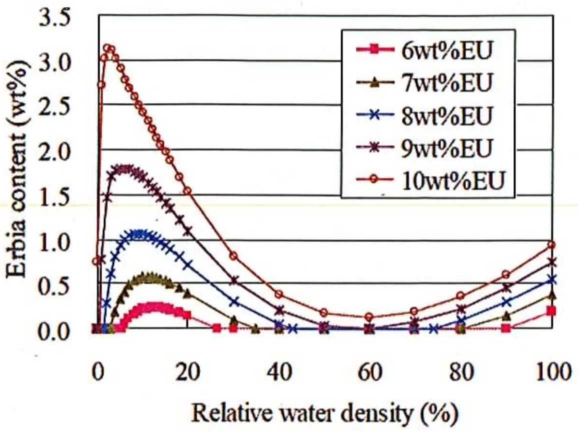


FIG. 17. Calculated results of Erbia content of the fuel assembly storage rack.

4.4 ECOS diagram

Based on the above mentioned results, the Erbia content versus uranium enrichment is shown in Figure 18. This Figure has been named ECOS (Erbia **CO**ntent for **S**ub-criticality judgment) diagram. The area above the curves shown in the ECOS diagram is judged to be sub-critical.

As shown in Figure 18, the rapid increase of required Erbia content for fuel assembly storage rack is caused by the repeated geometry in the hard spectral condition as mentioned in the previous section.

Refer to the feasibility study by the authors on the Er-SHB fuel loaded PWR core, the Er-SHB fuel is designed as around 6 wt% enrichment and Erbia content is 0.4 wt% [10]. It can be seen that the required Erbia content is around 0.3 wt% for uranium enrichment is 6 wt%. Therefore, the fuel design mentioned above (6 wt% enrichment with 0.4 wt% Erbia) can be judged as secure sub-critical.

Although the evaluated facilities are selected and modelled in sufficient consideration, it is desirable that all the facilities concerning Erbia credit should be evaluated in detail when it is introduced into a practical fuel cycle process.

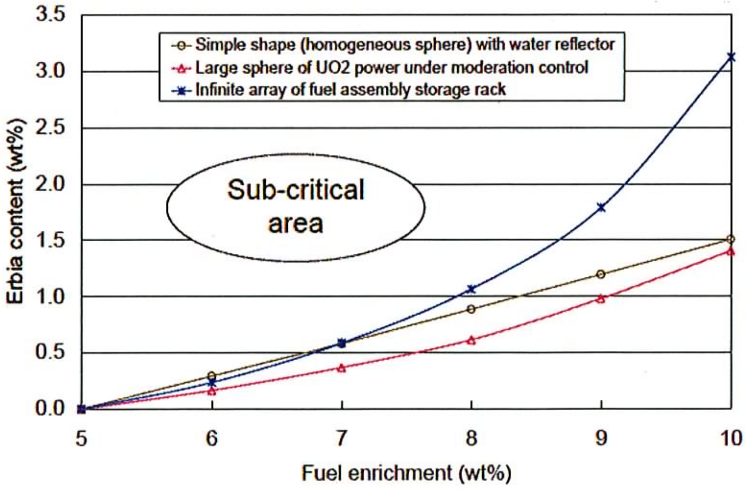


FIG. 18. Erbia content for sub-criticality judgment (ECOS) diagram.

5. Conclusions

In order to reduce the number of spent fuel assemblies and then to improve fuel cycle economics, the development project on Er-SHB fuel with high uranium enrichment is in progress. The program covers wide aspect of the development of LWR fuel such as critical experiments, criticality safety analysis using Erbia credit, physicochemical properties measurement of Erbia-bearing fuel pellet, and so on.

As the first topics of this paper, the outline and main concept of Er-SHB fuel was described. This concept represents adding low content (>0.2 wt%) of Erbia in all UO_2 powder, so that a reactivity of high enrichment (>5 wt%) fuel should be suppressed under that of current fuel assemblies, i.e. below 5 wt% enrichment. Since Erbia is mixed into UO_2 powder at the time after a re-conversion process, the advantage of negative reactivity credit of Erbia can be taken in the most criticality safety issues appearing after the re-conversion process.

Secondly, the measurement and analysis results of a series of fully Er-loaded core experiments are presented. A series of these experiments are appropriately cover the features of Er-SHB fuel, such as the range of uranium enrichment of 5 to 10 wt%, fully Erbia loaded into the core of which content is rather low (below 1.12 wt%), a moderator ratio varies from 48 to 274, which can represent various neutron spectra from hard to soft. These experimental data will be so efficient to validate neutronic analysis codes, which are used for criticality safety analysis of Er-SHB fuel.

Thirdly, criticality safety analyses are performed with introducing the concept of the Erbia credit. Based on the comprehensive criticality safety analyses for typical geometries, the Erbia content versus uranium enrichment is determined as the ECOS (**E**rbia **CO**ntent for **S**ub-criticality judgment) diagram. Er-SHB fuel is judged to secure sub-critical based on the ECOS diagram.

Consequently, the feasibility of Er-SHB fuel concept is confirmed from the nuclear physics point of view. Another development items, such as;

- Fabrication test and physicochemical properties measurement of Erbia-bearing fuel pellet
- Core design using the Er-SHB fuel assemblies
- Applicability of burnup credit for the Er-SHB fuels
- Effect on the back-end stream such as disposal of high-level radioactive waste (HLW)

are also investigated in the development program.

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