Research Activities of JAEA Considering the Future Needs of Japan in Burnup Credit Implementation

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1. Background

The burnup credit (BUC) can be applied to the criticality safety design of nuclear facilities and transport casks handling the spent nuclear fuel (SNF). BUC also defines criticality safety control procedures for the operation of such facilities. Introduction of BUC needs two major functions as shown in Fig.1, i) estimation of SNF condition, i.e. its isotopic composition of fuel region, and ii) calculation of the neutron multiplication factor using the SNF composition. The burnup calculation predicts the SNF composition and it should be validated by using the post irradiation examination (PIE) data. The neutron multiplication factor is computed by a criticality analysis code using given material composition and its geometrical shape. The criticality benchmark data based on critical experiments such as the data in the handbook of the International Criticality Safety Benchmark Evaluation Project (ICSBEP)[1] are valuable for validation of the codes.

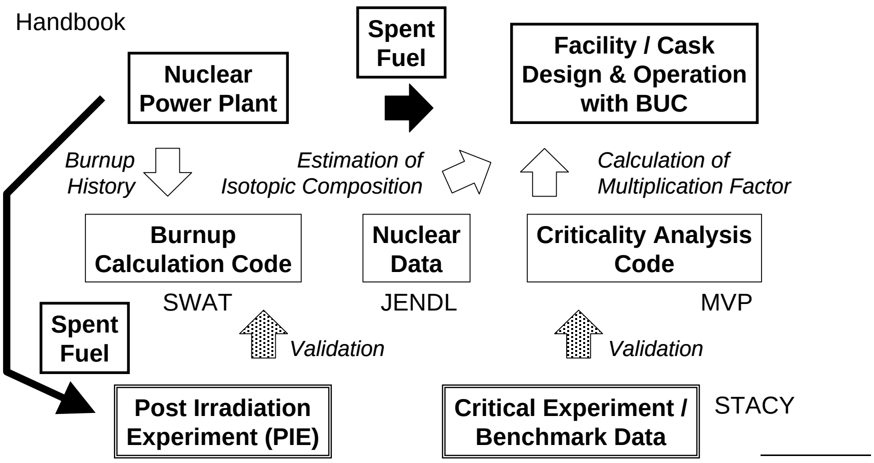

Fig. 1 Hierarchy of BUC technologies

The Japan Atomic Energy Agency (JAEA) and the former Japan Atomic Energy Research Institute (JAERI) have been contributing to each technical field to establish BUC. The critical experiment facility STACY has been used to measure critical volumes of the low enriched uranium nitrate solution.[2] The obtained data in STACY have been precisely evaluated and provided to ICSBEP. In order to provide criticality safety guide, criticality safety handbooks[3,4] and data collections[5] have been published to describe principles, typical procedures and standard numerical values of criticality safety limits necessary for the criticality safety design and controls, using the continuous-energy Monte Carlo code MVP[6] and the evaluated nuclear data library JENDL-3.2[7]. Considering the importance of well-qualified burnup calculation, the integrated burnup code system SWAT[8] that utilizes MVP and MCNP[9] has been developed. The other technical capabilities are to conduct post irradiation examinations (PIEs) of SNF from light water reactors (LWRs).

In Japan, BUC has been applied to quite limited area as indicated in Fig.2 No BUC is taken in the criticality safety design of SNF pools of nuclear power plants (NPPs). The SNF transport casks currently used and the dual-purpose dry casks to be used for the off-site storage also have the design that allows the handling of fresh fuel.

The criticality safety design and control with BUC has been implemented, with the consideration of actinide (uranium and plutonium) content change due to burnup, only in the Rokkasho reprocessing plant.[10] First, there is a maximum residual ^{235}U enrichment limit of SNF assemblies which the plant can accept. Just after unloading from a transport cask, every SNF assembly is measured with the burnup monitor to confirm that the assembly is acceptable. The monitor measures a burnup, from which a residual ^{235}U enrichment is derived using an initial ^{235}U enrichment. Then one of two types of storage racks that have different design conditions is selected based on the residual ^{235}U enrichment of the SNF assembly.[11] In the dissolving process, the measured burnup and the initial ^{235}U enrichment is used to judge necessity of the gadolinium (Gd) soluble poison.

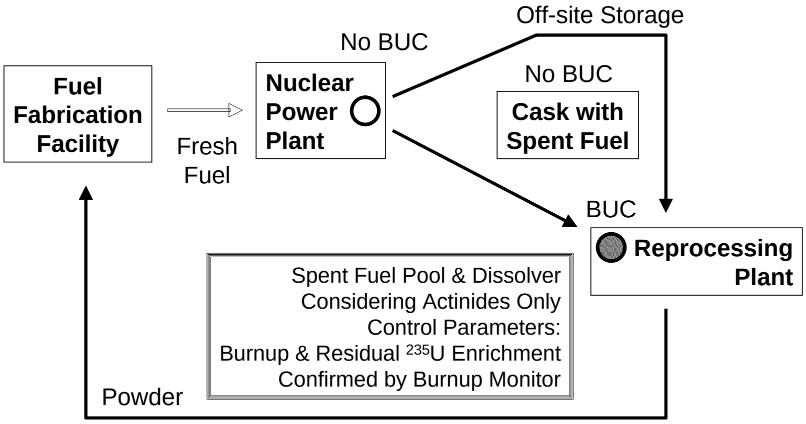

Fig. 2 BUC seen in the nuclear fuel cycle of Japan

2. JAEA Activities

2.1 STACY Experiment

STACY is a critical assembly installed in the Nuclear Fuel Cycle Safety Engineering Research Facility (NUCEF) at the Nuclear Science Research Center of JAEA, where critical experiments have been conducted to accumulate critical safety benchmark data for the criticality safety design of reprocessing facilities. Uranyl nitrate solutions whose ^{235}U enrichment (EU) were 10% and 6% were used for homogeneous experiments. Heterogeneous experiments were also con~~ducted simulating~~ a dissolver using the uranyl nitrate solution (6% EU) and PWR-type UO_2 fuel rods (5% EU).[12] Relating to the introduction of BUC considering the accumulation of fission products (FPs), reactivity worths of typical FP elements were measured using the heterogeneous system.

The STACY heterogeneous core consisted of, as shown in Fig.3, solution fuel, fuel rods and a core tank containing them. The core tank was made of SUS304 stainless steel and has an inner cavity size of 59 cm diameter and 150 cm height. There was also supporting structure made of Zircaloy-4 such as grid plates and tie rods inside the core tank, where 333 fuel rods were arrayed in a square lattice of 1.5 cm interval.

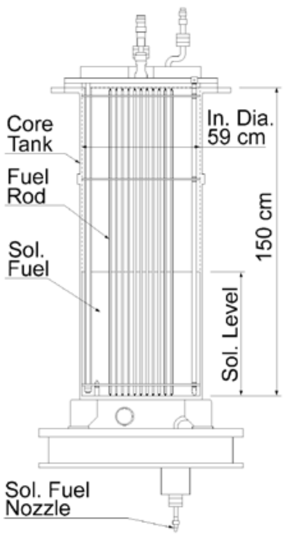

Fig.3 STACY heterogeneous core

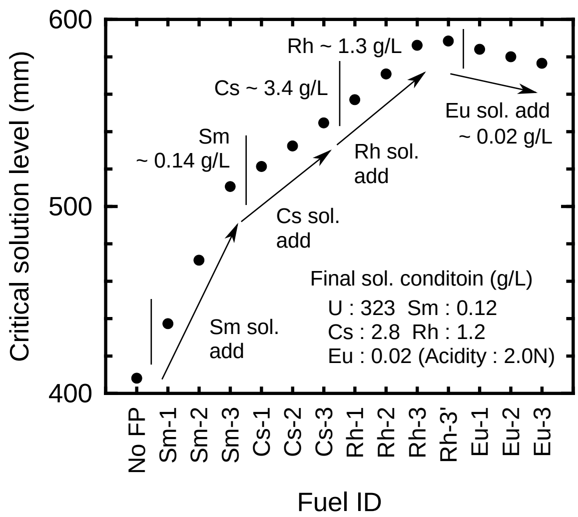

Fig.4 Critical solution level variation depending on FP-element contents (water reflected core)

Samarium (Sm), cesium (Cs), rhodium (Rh) and europium (Eu) which had the natural isotopic compositions were successively added to the uranyl nitrate solution whose uranium concentration was about 330 g/L, and critical volume measurement was performed after each addition. The variation of critical solution level depending on the fuel solution conditions is plotted in Fig.4. The critical volume change reflected increase of neutron absorption by the elements and the effects could be indicated as reactivity worths as shown in Fig.5 and Fig.6. [13,14]

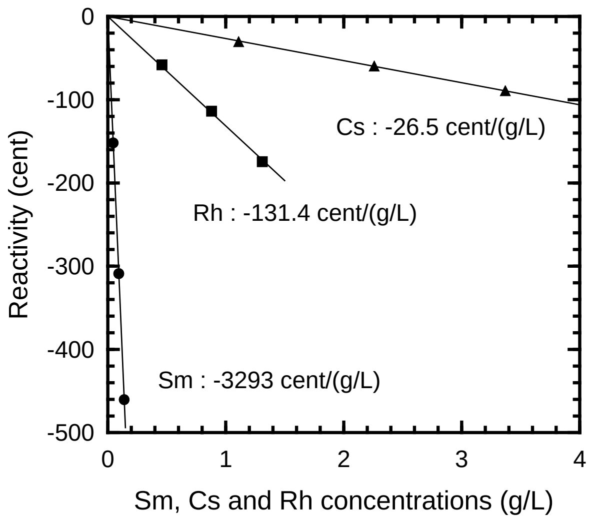

Fig.5 Reactivity worths of Sm, Cs, and Rh

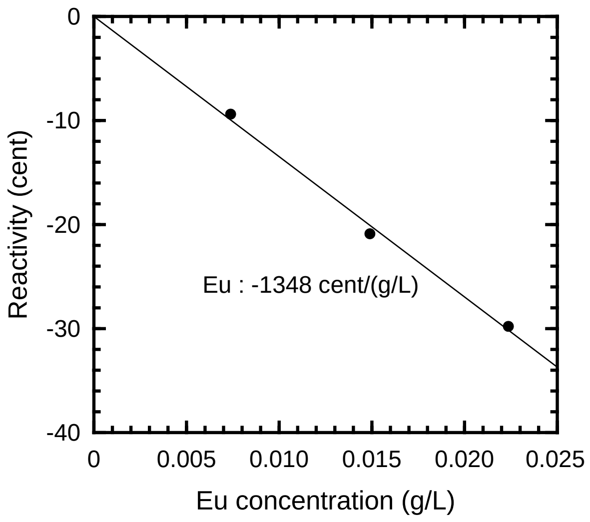

Fig.6 Reactivity worth of Eu

Another series of experiments were also performed using Gd instead of FP elements to measure precisely the reactivity worth of the Gd soluble poison used in a dissolver. Fig.7 shows relation between the Gd concentration in fuel solution and the measured critical solution level. [15]

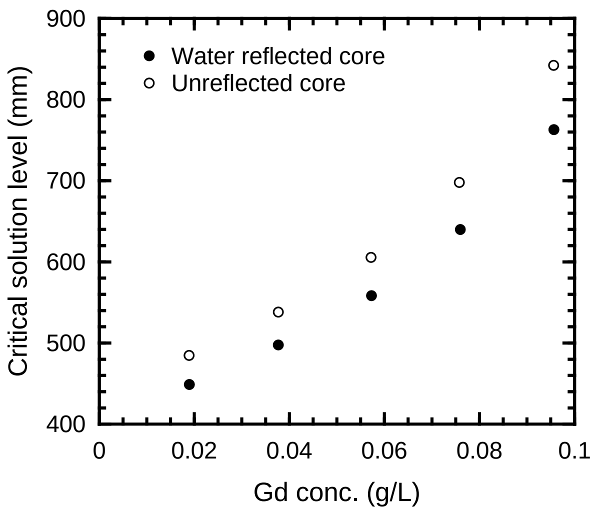

Fig.7 Critical solution level variation depending Gd concentration

These benchmark data are expected to contribute for realizing more sophisticated BUC considering FP accumulation and economical use of Gd in a dissolver.

2.2 Code Development

SWAT is an integrated burnup calculation code which combines the neutronics calculation code SRAC, which is widely used in Japan, and the point burnup calculation code ORIGEN2. It has been used to evaluate the composition of the uranium, plutonium, minor actinides and FPs in SNF.

Development of a new version of SWAT code, named SWAT-3.1, has been carried out in order to allow users to utilize the continuous energy Monte Carlo code MVP, which was developed by the former JAERI, as well as MCNP5.[16] This enables users to treat arbitrary fuel geometries with a few approximations when generating the effective cross section data to be used in the burnup calculation. This version was applied to the analyses of OECD/NEA Burnup Credit Phase IIIB Benchmarks and PIE data, which concluded that SWAT-3.1 could predict the isotopic composition with better accuracy and flexibility because of the introduction of continuous energy Monte Carlo codes.

2.3 Post Irradiation Examinations (PIEs)

JAEA has also capability to conduct PIE of LWR SNF. A PIE program is currently in progress under the entrustment of Japan Nuclear Energy Safety Organization (JNES). Several samples were taken from two 9×9 BWR assemblies and are going to be analyzed for quantifying typical FP isotopes effective for BUC (Sm, Cs, Nd, Rh, Gd, etc.). This examination also aims at practice in future PIEs of MOX fuel.

2.4 Handbooks

The first nuclear criticality safety handbook of Japan was published in 1988 to show the principles for addressing criticality safety and the methods for analytical evaluation.[3] Mentioned in this publication were i) the basic methodology for criticality safety, the terminology used, the methods to secure subcriticality, and the standards used to determine subcriticality, ii) examples of models that are appropriate for safety analyses of complex systems, and iii) specific methods of safety analysis and evaluation. The data collection part consisted of data needed for calculation of atomic number density, parameters of nuclear characteristics for various nuclear fuel compositions, criticality data for infinite systems, criticality data for single units and data needed for analysis of multiple units, which were evaluated using the criticality safety analysis code system JACS[17].

The 2nd version of the criticality safety handbook of Japan followed in 1999, in which new chapters are added into the first version to exemplify safety margins related to modeled dissolution and extraction processes, and to describe evaluation methods and alarm system for the criticality accident.[4]

The data collection part of the handbook was completely renewed and released as the 2nd version in 2009 using numbers produced by the new code system, MVP and the latest library JENDL 3.2. This version newly provides criticality data on homogeneous U-H_2O and UF_6-HF, which were not cited in the previous version.

Preliminary version of a guide introducing burnup credit was published as a report from JAERI in 2001.[18] Efforts for translating the original Japanese report into English are nearly finalized, and those for updating its texts and data are underway.

3. Expected Trend in Future

It is expected that the utilization of LWR will last until the FBR and its fuel cycle becomes practicable and settled. This means that it must be continued to improve efficiency of the electricity generation with LWR and its fuel cycle. One option may be a longer operation period between fuel loading and maintenance works, which will be helped by employing a new uranium fuel design with higher initial ^{235}U enrichment. It may be beyond the current limitation of 5%. Must be considered in this case is introduction of BUC for SNF, for example, into the transportation or the NPP on-site storage in cooling water, because it would not be feasible to handle SNF with the assumption that it were fresh fuel.

To develop the BUC application with a consideration of the reactivity change due to FP build up, followings could be discussion points. Applicants, which may be NPP operators, should demonstrate their capability of burnup calculation to predict, with enough accuracy and reliability, isotopic compositions of FPs as well as actinides in SNF. Although the current management technology of reactor cores may be advanced enough from a view point of the reactor operation, it may be necessary to prove the computation methods to calculate precise amounts of some FPs and actinides which build up or deplete in both periods of the operation and the cooling. In parallel, improvement of measurement technique have to be studied to establish a method to check reactivity of SNF based on burnup, FP accumulation, residual fissile contents and so on. Priorities have to be discussed, as well, to determine which of the calculation or the measurement could be a primary method to judge the BUC.

Some of the research and development (R&D) works need an incentive of utilities. It is believed that the future trend of the fuel design mentioned above must call their attentions to the BUC applications. In the same time, research institutes such as JAEA must maintain R&D capabilities including critical experiments, PIEs, and computational works so that they can respond timely to requirements by nuclear industries and regulatory bodies.

4. Conclusion

Although there is, currently in Japan, only one facility, a reprocessing plant, where BUC is taken into its criticality safety design, it is expected that BUC have to be considered in wider scenes of the nuclear fuel cycle such as the SNF transportations and the off-site storage using dual-purpose casks. This is because it must be continued to improve the efficiency of electricity generation with LWR using uranium as far as the utilization of LWR might last for more than several decades, which is going to introduce a higher initial ^{235}U enrichment into the uranium fuel design, very probably beyond 5%.

JAEA is conducting R&D activities including critical experiments, PIEs and analytical researches to provide appropriate options of the BUC introduction, from which nuclear industries and regulatory bodies of Japan could select a BUC method. The activities are going to be shared with other institutes in Japan as well as international organizations such as OECD/NEA.

Acknowledgement

The STACY experiments with FP described in Section 2.1 was conducted by the former JAERI under the contract with the Ministry of Education, Culture, Science and Technology of Japan.

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