# CRITICALITY SAFETY STUDIES RELATED TO ADVISORY MATERIAL FOR THE IAEA REGULATIONS

*H. Okuno (1), T. Sakai (2)*

*(1)* JAERI, Tokai-mura, Naka-gun, Ibaraki-ken, 319-11, Japan
*(2)* The Japan Research Institute, Ltd., 16 Ichibancho, Chiyoda-ku, Tokyo, 102, Japan

## SUMMARY

Criticality safety studies are reviewed related to Advisory Material for 1996 Edition of the IAEA Regulation for the Safe Transport of Radioactive Material. Criticality calculations based on the perturbation theory are given with and without small variations in fuel concentration for $UO_2$-$H_2O$ and $PuO_2$-$H_2O$. They show that variations in fuel concentrations of 5% can give at most a 0.4%Δk/k increase in the neutron multiplication factor. Heterogeneity effect of fuel is examined for arrays of low-enriched $UO_2$ fuel particles immersed in water. In case of fuel particles having a diameter of 50 μm, the relative increase in the neutron multiplication factor is shown to be less than 0.1%Δk/k. Isolation thickness of water is discussed in term of the Reflector Factor, which is defined as a relative increase in the neutron multiplication factor of fuel with finite thick isolator to that with infinite thick isolator. Thirty cm is regarded as a practical value for isolation thickness of water.

## INTRODUCTION

IAEA Regulation for the Safe Transport of Radioactive Material was revised and published in 1996. Advisory Material for the Regulation is prepared for publication. The present paper reviews our studies on nuclear criticality safety, especially for (1) uniformity, and (2) homogeneity of fuel, and (3) isolation thickness of water. It intends to supply with additional information to the Advisory Material.

Concerning the uniformity of fuel concentration on nuclear criticality safety, the following description is given in the item 672.3 of the Advisory Material: "Concentrations can also vary throughout the material, however, variations in concentrations of the order of 5% should not compromise criticality safety." As there are no proper references regarding to this statement to the best of our knowledge, we have made numerical calculations based on the perturbation theory to give examples to this empirical statement.

Latticing of uranium fuel in a moderating medium is precluded from homogeneity. The same item of the Advisory Material refers to an agreement in ANSI/ANS-8.12-1987 that the homogeneous mixtures and slurries are those in which the particles constituting the mixture are uniformly distributed and have a diameter no larger than 127 μm (0.005 in). This value was based on the tradition among experimenters. We made numerical calculations for an infinite cubic array of low-enriched $UO_2$ small spherical particles immersed in water.

Thick layers of full-density water between fuel packages can reduce neutron interaction in arrays to an insignificant value. The item 671.4 of the Advisory Material refers to about 30 cm as a typical value for the isolation thickness of water. We introduced a function which represents a degree of neutron interaction in arrays, and discussed the isolation thickness of water.

## UNIFORMITY

An increase $\delta\rho$ in reactivity due to a variation $\delta u(\mathbf{r})$ in fuel concentration is expressed as an integration over the entire fuel space $V$:

$$\delta\rho = \int_V d\mathbf{r} I_f(\mathbf{r})\delta u(\mathbf{r}) - \lambda\int_V d\mathbf{r}\delta u(\mathbf{r})\ , \tag{1}$$

where $\lambda$ is the Lagrange's multiplication factor. The second term assures that the average fuel concentration is constant.

The weighting function $I_f(\mathbf{r})$ to the variation in fuel concentration is called a fuel importance function. The G-grouped expression for the fuel importance function is given as (Okuno and Sakai 96)

$$I_f(\mathbf{r}) = \sum_g \Phi_g^+\left[\frac{1}{k}\chi_g \sum_{g'} \nu_{g'}\frac{\partial\Sigma_{fg'}}{\partial u}\Phi_{g'} - \frac{\partial\Sigma_{Rg}}{\partial u}\Phi_g + \sum_{g'\neq g}\frac{\partial\Sigma_{sg'g}}{\partial u}\Phi_{g'}\right] \Bigg/ \sum_{g,g'}\int d\mathbf{r}\Phi_g^+\chi_g\nu_{g'}\Sigma_{fg'}\Phi_{g'}\ . \tag{2}$$

A computer code OPT-SN was developed to calculate the increase in the neutron multiplication factor for taking into account of optimum nonuniform distribution of fuel concentration. The code originally permits fuel concentration to vary from 0 to the theoretical density. In this study, however, the upper and lower bounds of fuel concentration are set to ±5% variations to the average which kept constant.

Table 1 Specifications of fuels investigated for the nonuniformity effect on reactivity

| Fuel Type | $UO_2$-$H_2O$ | $PuO_2$-$H_2O$ |
|---|---|---|
| Isotopic Composition [wt%] | $^{235}U$:$^{238}U$=5:95 | $^{239}Pu$:$^{240}Pu$:$^{241}Pu$=71:17:12 |
| Fuel Geometry | Slab | |
| Thickness of Slab [cm] | 10 | 4 |
| Fuel Concentration [gHM/cm$^3$] | 0.5 - 4.0 | 0.1 - 4.0 |
| Reflector | 30-cm-Thick Water | |

Note: HM = Heavy Metal

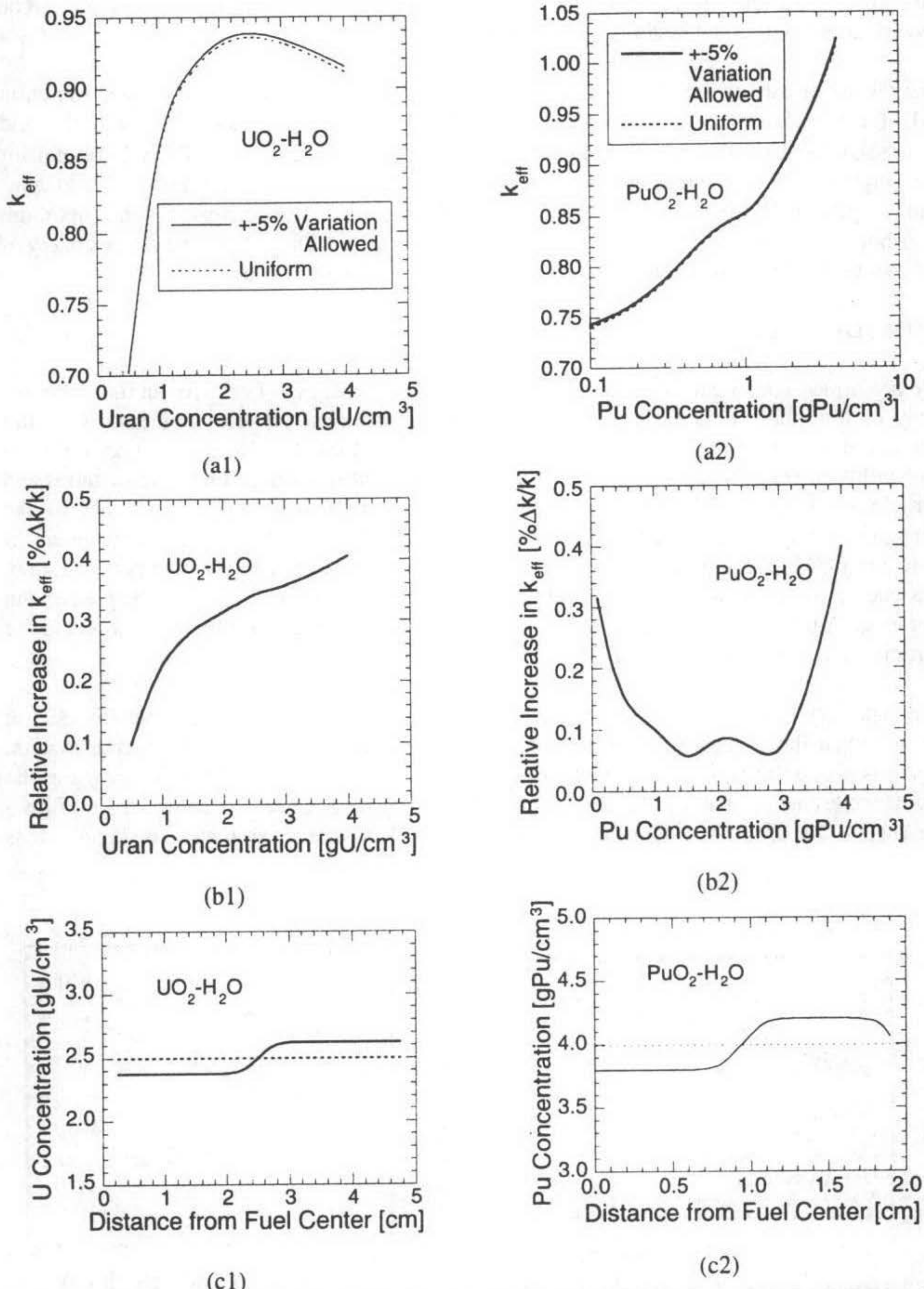


Fig.1 The neutron multiplication factor $k_{eff}$ was obtained as (a1) for $UO_2$-$H_2O$, and (a2) for $PuO_2$-$H_2O$ with the uniform distribution (dotted line) and the optimum distribution permitting ±5% variations of fuel concentrations (solid line). The relative increase in $k_{eff}$ was plotted in (b1) and (b2). The optimum distributions of fuel concentration which give the maximum $k_{eff}$ with this constraint were shown in (c1) and (c2).

The code was applied to two fuel systems: (1) $UO_2$-$H_2O$, and (2) $PuO_2$-$H_2O$. The specifications of the fuel systems are shown in Table 1.

The results of calculations are summarized in Fig.1. The rate of increase in $k_{eff}$ is shown in (b1) for $UO_2$-$H_2O$, and in (b2) for $PuO_2$-$H_2O$ systems. It has values between 0.1 and 0.4 %Δk/k for $UO_2$-$H_2O$ system and between 0.05 and 0.4 %Δk/k for $PuO_2$-$H_2O$ system for the range of fuel concentration investigated. The $k_{eff}$ itself has its maximum at 2.5 gU/cm$^3$ and 4 gPu/cm$^3$, for $UO_2$-$H_2O$ and $PuO_2$-$H_2O$ systems, respectively. The optimum distributions of fuel we obtained are shown in (c1) and (c2). They show that the periphery of the fuel region has higher concentration of fuel relative to other regions.

## HOMOGENEITY

We performed numerical calculations of the neutron multiplication factor for an infinite cubic array of low and medium $^{235}$U-enriched $UO_2$ small spherical particles immersed in water (Okuno et al. 1994). The calculations were made based on the ultra-fine energy collision probability method for various combinations of enrichments, water-to-fuel volume ratios and particle sizes. The relative change in the infinite multiplication factor to that of the homogeneous system Δk/k, which is a measure of and defined as the heterogeneous effect, is shown in Fig. 2. The water-to-fuel volume ratio, or the cell-averaged uranium concentration, was chosen to get the optimum moderation in homogenized system. It should be pointed out that even in the 40 wt% enriched uranium system, the heterogeneity effect was observed for particles in the diameter less than 2mm.

The four factor analysis was made for 5 wt% $^{235}$U-enriched $UO_2$-$H_2O$ system (Fig.3). It revealed that the change in the neutron multiplication factor from the homogeneous system, which is proportional to the fuel particle size up to 1 mm, is dominated by the change in the resonance escape probability of neutrons. The heterogeneity effect for cubic arrays of low-enriched $UO_2$ particles in diameter of 1mm immersed in water was plotted in Fig.4. It is

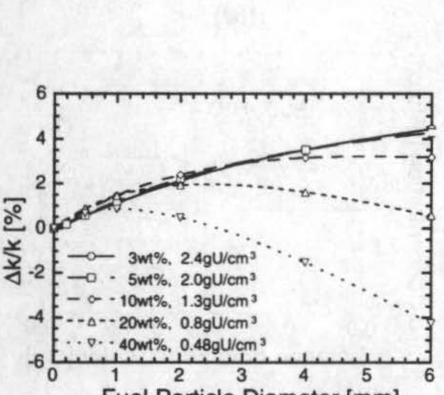


Fig.2 Heterogeneity effect for arrays of low and medium $^{235}$U-enriched $UO_2$ particles immersed in water, as a function of fuel particle diameter

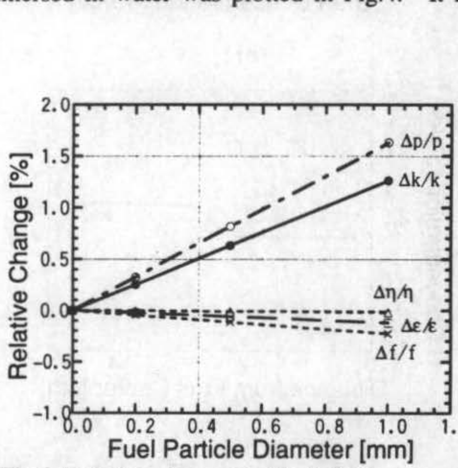


Fig.3 Relative changes in the infinite multiplication factor and its four factors for cubic arrays of 5 wt% $^{235}$U-enriched $UO_2$ particles immersed in water

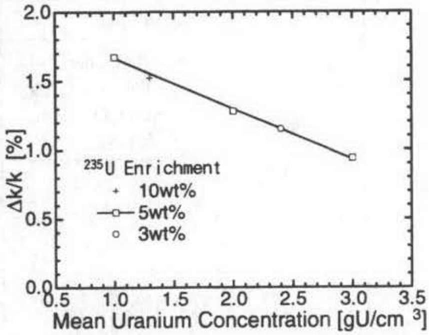


Fig.4 Heterogeneity effect for arrays of low $^{235}U$-enriched $UO_2$ particles in diameter of 1 mm immersed in water, as a function of mean uranium concentration

well expressed as a linear function of the average uranium concentration, which rarely depends on uranium enrichment up to 10 wt%.

These results show that the heterogeneity effect is less that 0.1% for 5wt% $^{235}U$-enriched $UO_2$-$H_2O$ system, e.g., when the fuel particle size is less than 50μm; thus it can be treated as homogeneous.

## ISOLATION BY WATER

In order to study the isolation thickness, the Reflector Factor (*RF*), which represents a degree of neutron interaction in arrays, was defined by Eq. (3) in the Nuclear Criticality Safety Handbook of Japan.

$$RF = \frac{k(T) - k_s}{k_s}, \tag{3}$$

where

$k(T)$: The neutron multiplication factor of the system where isolator thickness is $T$ and the nuclear fuel systems on the opposite side of the isolator are assumed to be the same.

$k_s$: $k(T \to \infty)$, which is the neutron multiplication factor where the object nuclear system is surrounded by an infinitely thick isolator.

The nuclear fuel system may be either a single unit or a multiple unit. Two examples of numerical calculations are depicted using this function:

(1) Fig. 5 shows the results for three configurations: 2×1, 3×3 and infinite arrays of a cylinder immersed in water (Sakai and Naito, 1987). All the arrays are 2-dimensional, and the other directions (axial directions) are reflected with fully thick water reflectors. Each cylinder with neglected wall thickness has a 30-cm-diameter and 100-cm-height, and contains 5wt% $^{235}U$-enriched $UO_2$-$H_2O$ (2gU/cm$^3$). The *RF* decreases monotonically as the thickness of the water isolator increases.

(2) Fig. 6 shows the results for the changes in *RF* where the following three types of infinite slab fuel are isolated with water: $^{235}U$ metal (thickness: 2cm), homogeneous $^{235}U$-$H_2O$ (uranium concentration: 0.1 gU/cm$^3$, thickness: 7.5 cm), and homogeneous U-$H_2O$ ($^{235}U$ enrichment: 5 wt%, uranium concentration: 2 gU/cm$^3$, thickness: 12 cm).

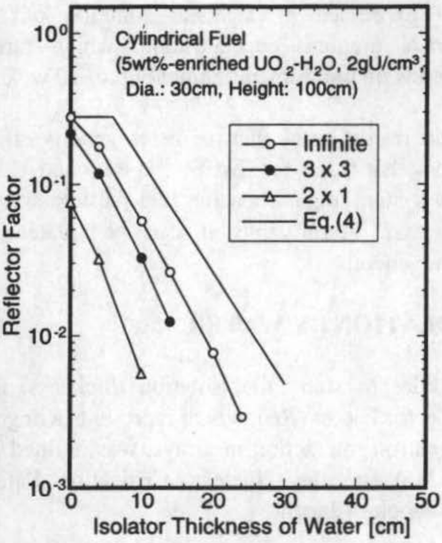


Fig.5 Changes in Reflector Factor (*RF*) versus the thickness of a water isolator for 2-dimensional arrays of a cylindrical fuel immersed in water

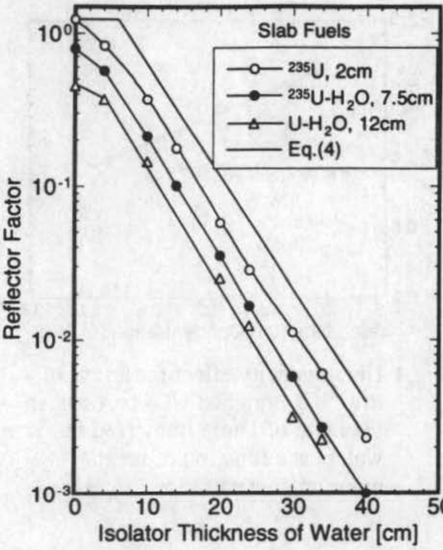


Fig.6 Changes in Reflector Factor (*RF*) versus the thickness of a water isolator for arrays of infinite slab fuels immersed in water

As is evident from Fig. 6, despite the kind of fuel, *RF* decreases exponentially with an increase in isolator thickness. Except the cases of thin isolator, the gradient of this decrease is approximately the inverse of the neutron migration length in water (1/5.93 $cm^{-1}$). The gradient of *RF* in the junction of fuel and isolator becomes gradual because of the increased direct leakage of the neutrons from the fuel region. The *RF* decreases exponentially when the isolator thickness becomes larger than the neutron migration length. Considering the above discussion, *RF* can be estimated using a simple formula:

$$RF = \left(\frac{k(0)}{k_s} - 1\right) \cdot exp\left(1 - \frac{T}{M}\right) \quad \text{for } T>M, \qquad (4)$$

and

$$= \frac{k(0)}{k_s} \quad \text{for } T \le M,$$

where

*k*(0): k(T→0), which is the neutron multiplication factor of the system where the isolator thickness becomes zero and the nuclear fuel system contact with each other,

*T*: Isolator thickness, and

*M*: Migration length of neutron in isolator (= 5.93cm for water).

The simple estimate of *RF* expressed by Eq. (4) becomes about 2% for the 2 cm thick $^{235}U$ slab case. This is typically the most conservative case for the neutron interaction through 30-cm-thick water isolator. Indeed, looking back to Fig. 5, a 30-cm-thick water isolator gives insignificant (about $10^{-3}$) value for *RF* for arrays of cylindrical fuels. Considering the above examples, 30 cm should be regarded as a practical value for the isolation thickness of water.

## CONCLUSIONS

(1) Variations in fuel concentrations of 5% can give a 0.4%Δk/k increase in the neutron multiplication factor at most.
(2) Even though there is latticing of uranium fuel in water moderator, it can be regarded as homogeneous when the fuel particle size is very small. For example, in case of fuel particles having a diameter of 50 μm, the relative increase in the neutron multiplication factor is less than 0.1%Δk/k.
(3) Thirty cm is regarded as a practical value for isolation thickness of water.

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