# ADVANCED CONCEPT OF REDUCED-MODERATION WATER REACTOR (RMWR) FOR PLUTONIUM MULTIPLE RECYCLING

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## ABSTRACT

An advanced water-cooled reactor concept named the Reduced-Moderation Water Reactor (RMWR) has been proposed to attain a high conversion ratio more than 1.0 and to achieve the negative void reactivity coefficient. At present, several types of design concepts satisfying both the design targets have been proposed based on the evaluation for the fuel without fission products and minor actinides. In this paper, the feasibility of the RMWR core is investigated for the plutonium multiple recycling under advanced reprocessing schemes with low decontamination factors as proposed for the FBR fuel cycle.

*Keywords : Advanced Water Reactor, Reduced-Moderation, High Conversion Ratio, Negative Void Reactivity Coefficient, Plutonium Multiple Recycling*

## 1- INTRODUCTION

An advanced water-cooled reactor concept named Reduced-Moderation Water Reactor (RMWR) is under development at JAERI in cooperation with JAPC and TEPCO with the technical support from the Japanese LWR vendors. The reactor aims at achievement of a high conversion ratio more than 1.0 with plutonium (Pu) mixed oxide (MOX) fuel, based on the well-experienced water-cooled reactor technology. Such a high conversion ratio can be attained by reducing the moderation of neutrons, *i.e.* reducing the water fraction in the core. This type of reactor is favorable to realize the long-term energy supply with the uranium resources, the high burn-up / long operation cycle achievement or the multiple recycling of Pu. The reduced neutron moderation by the water results in a similar neutron spectrum to that in a sodium-cooled fast breeder reactor (FBR), even in a water-cooled reactor. Another important design target for the RMWR is to achieve the negative void reactivity coefficient. This is one of the important characteristics of the currently operated light water reactors (LWRs), especially from the safety point of view. However, the negative void reactivity coefficient and the high conversion ratio are in the trade-off relation in the reactor design, and this gives a difficulty to be overcome in the design of the RMWR.

At present, several types of basic design concepts satisfying both the main design targets mentioned above have been proposed by the authors [1],[2] under both the boiling water reactor (BWR) type concept and the pressurized water reactor (PWR) type one. The common design characteristics are the tight-lattice fuel rod configuration and the short core. The former is to attain the high conversion ratio and the latter is for the negative void reactivity coefficient. Additionally, the axial, *i.e.* upper, lower or internal, or the radial blankets made of the depleted $UO_2$ (DU) are also introduced by necessity for both purposes mentioned above.

For the RMWR utilization, the multiple recycling of Pu is the essential basis under the MOX spent fuel reprocessing fuel cycle. On this point, the fuel cycle proposed for FBRs might be adopted also for the RMWR. The advanced reprocessing schemes currently proposed for the FBR fuel cycle are, however, in general with the low decontamination factors (DFs) and allows some amount of fission products (FPs) and minor actinides (MAs) to remain in the MOX fuel. Since they are expected to give negative effects on the core performances and the conversion ratio of the RMWR is just more than 1.0, it is necessary to investigate the core performances of the RMWR under the multiple recycling situation with such the advanced fuel reprocessing schemes in relatively low DFs.

## 2- BASIC DESIGN IDEAS FOR RMWR

The main design goals for the RMWRs are the following two points as already mentioned above;
(1) High conversion ratio more than 1.0
(2) Negative void reactivity coefficient
The former is indispensable for the long-term energy supply with uranium resources under the multiple recycling of Pu, and is also important for the high burn-up and long operation cycle achievement due to the smaller burn-up reactivity. The latter is common safety characteristic in the current LWRs and is considered to be also required for the RMWRs, because the RMWRs exist on the extension of the experienced LWRs technology following the same safety philosophy.

In order to achieve the high conversion ratio, the volume of the moderator, *i.e.* water, should be reduced. For this purpose, the tight-lattice fuel rod arrangement is commonly adopted. The triangular lattice with a narrow gap between the fuel rods and/or the rods with a large diameter is typical for it. Installation of some special rods for water removal might be another idea. Especially for the BWR-type reactor design, increase in the core void fraction is another realistic technique to be used.

To satisfy the requirement of the negative void reactivity coefficient, neutron leakage should be increased when the void is generated or increased in the core. The short core design is common technique for it. The blanket region could be adequately used to increase neutron absorption. Some streaming mechanism might be also used to promote neutron leakage effect.

The above two design goals are attained by appropriately combining the basic techniques described above and by keeping a balance among them. Conceptual designing of the RMWR core is based on these general basic ideas as described in the following.

## 3- CONCEPTUAL DESIGN OF RMWR

In our design study, some different core designs have been investigated based on the different basic ideas described above. That is, there are some design possibility in adopting and combining the above basic ideas. At present, we have investigated three different types of core design under the BWR-type reactor concept [1], and two types for the PWR-type [2]. In this section of the paper, only one design out of them are presented in the following to give the general idea on the RMWR with some major core characteristic information.

The present core aims at as high conversion ratio as possible with 1,000MWe class power output. However, an attainable value was expected around 1.1 at most based on previous research information [3]. In order to achieve a very high conversion ratio, the core consists of hexagonal fuel assemblies with triangular tight-lattice configuration as shown in Figure 1. Y-shaped control rods with the follower structure are introduced as shown in the figure at the ratio of one unit for three fuel assemblies.

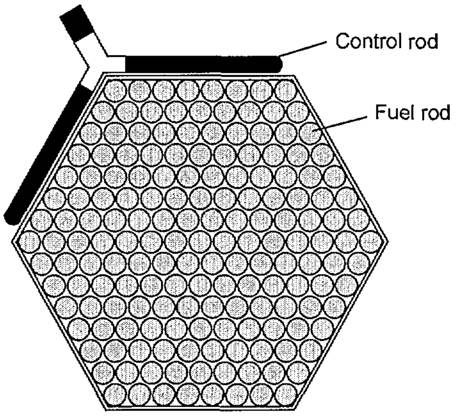

*Figure 1 : Schematic of fuel assembly*

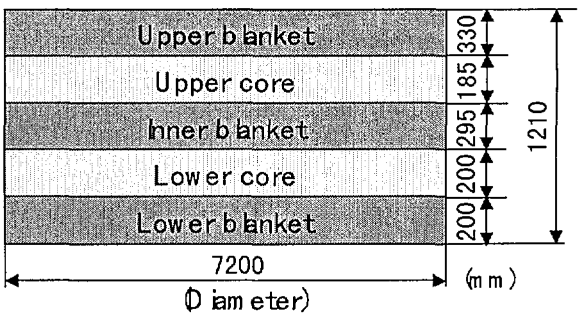

*Figure 2 : Vertical cross section of core*

The pitch of the assembly is about 220mm. The diameter of the fuel rods is 14.5mm and the gap between rods is kept at 1.3mm, which is considered to be a tentative limit from the zircaloy cladding structure and the heat removal points of view. The core average void fraction is significantly increased to 70 % in this design.

Resultantly, the effective volume ratio of the water to the fuel (*Vm/Vf*) is reduced extremely to about 0.17 in the present design, trying to attain a high conversion ratio.

To obtain negative void reactivity coefficients, the core or seed is extremely shortened to about 200mm high and two core parts are piled up with an internal blanket region. Adding the upper and lower blanket regions, the total core region has the five-layer structure in the axial direction as shown in Figure 2. This type of core arrangement was named the double-flat core and was initially proposed for a PWR-type high conversion reactor core design [4].

The fuel rod consists of MOX pellets and the zircaloy cladding. The average fissile Pu content in the seed regions is 18 % and the base material is the depleted $UO_2$ as in the blanket regions. There is a radial distribution in Pu contents of five levels in the assembly to reduce the local peaking less than 1.04.

In the neutronics calculations, the group constants of the assembly are prepared in 190 groups by the Monte Carlo method coupled with the burn-up calculation [5]. The core calculation was performed by the three-dimensional void-power iteration method, treating each assembly separately.

Figure 3 shows one example from the calculational results. The axial relative power and the void fraction distributions in the core are presented. It is indicated the void fraction is already more than 30 %, suggesting heat generation in the lower blanket region. Major dimensions and characteristics of the core determined by the calculations are summarized in Table 1.

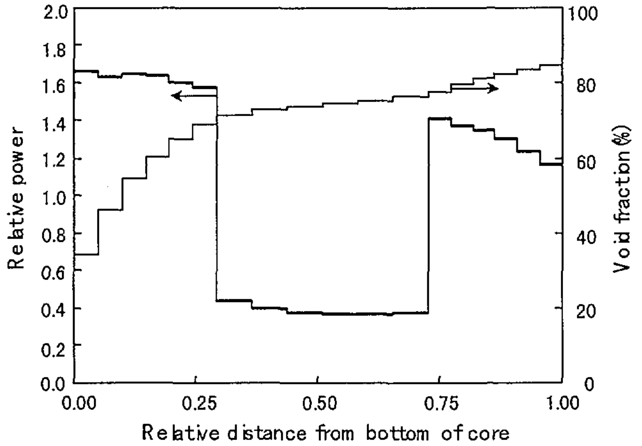

*Figure 3 : Core axial relative power and void fraction distribution*

*Table 1 : Major dimensions and characteristics of core*

| Item | Design value |
|---|---|
| Thermal power output (MWt) | 3,188 |
| Electric power output (MWe) | 1,100 |
| System pressure (MPa) | 7.2 |
| Core outer diameter (m) | 7.2 |
| Number of fuel assembly | 924 |
| Discharge burn-up for core part (GWd/t) | 45 |
| Core height (m) | 0.68 |
| Core mass flow rate ($10^4$t/h) | 1.3 |
| Core exit quality (%) | 55 |
| Core average void fraction (%) | 70 |
| Average fissile Pu content (wt%) | 18 |
| Conversion ratio at MOC | 1.10 |
| Fissile plutonium conversion ratio | 1.06 |
| Maximum linear power density (kW/m) | 55.8 |
| MCPR | 1.3 |
| Void reactivity coefficient ($10^{-4}$dk/k%void) | -1 |
| Operation cycle length (EFPM) | 14 |

The conversion ratio is calculated to be 1.1 at the middle of the equilibrium cycle, and the conversion ratio of the fissile plutonium is 1.06. The void reactivity coefficient evaluated is $-1\text{x}10^{-4}$dk/k/%void. The number of assembly necessary for 1,100MWe output is 924. The core outer diameter is somewhat large and is 7.2m, although this size is in the fabrication range of the reactor vessel. The core average burn-up excluding the upper and lower blanket regions is 45GWd/t and the cycle length is 14 months.

The maximum linear power density is 55.8kW/m, which is within the limit for the previously used 7 x 7 type fuel assembly of BWRs with the same large fuel rod diameter of 14.5 mm. The Minimum Critical Power Ratio (MCPR) is evaluated to be 1.3 under the normal operational conditions with the modified CISE critical power correlation [6]. The correlation was developed for the tight-lattice fuel assembly based on the CISE's critical quality *vs.* boiling length type correlation and some data on the critical heat flux experiments conducted with the tight-lattice test sections at the Bettis Atomic Power Laboratory in 1970s [7].

Safety analyses for the typical transients and accidents have also been performed for the present core design under nearly the same primary cooling system as in the ABWR, in which the internal pumps are utilized as the recirculation pumps. In the present design, the void reactivity coefficient is negative but smaller in absolute value than in the current BWRs. Therefore, the events, in which the core flow rate becomes small, become severe, bur the magnitude of decrease in MCPR is evaluated to be in the same level as in BWRs.

## 4- INVESTIGATION ON MULTIPLE RECYCLING

As mentioned in Section 1, the core performances under the advanced fuel reprocessing schemes proposed for the FBR fuel cycle [8] have been investigated. The results of the investigation are presented in the following. Advanced fuel reprocessing schemes, such as the advanced PUREX processes and the dry reprocessing ones, have been proposed to give much lower DFs than in the current PUREX process with the very high DFs around $10^6$, and hence, some amount of FPs and MAs are contained in the fresh fuel. Since they are expected to have negative effects on the core performances, such as the reactivity, the void reactivity coefficient and the conversion ratio, the effects should be evaluated considering them as the components of the fresh fuel under the Pu recycling situation. Up to now, the evaluation of the core characteristics presented in Table 1 has been performed for the fuel components obtained with the current PUREX reprocessing of the spent fuel from LWRs. That is, the amount of FPs and MAs in the fresh fuel is negligible in this case. This fuel composition is named the standard fuel composition in our study on the RMWR.

*Table 2 : TRU composition for MA effect study case*

| Item | | MA effect case | Standard case |
|---|---|---|---|
| Conditions | Origin core | BWR core ($UO_2$) | BWR core ($UO_2$) |
| | Discharge burn-up (GWd/t) | 45 | 45 |
| | Cooling time for reprocessing (y) | 5 | 5 |
| | Period after reprocessing (y) | 2 | 2 |
| TRU composition (wt%) | $^{237}$Np | 5.6 | 0.0 |
| | $^{238}$Pu | 2.4 | 2.7 |
| | $^{239}$Pu | 42.9 | 47.9 |
| | $^{240}$Pu | 27.2 | 30.3 |
| | $^{241}$Pu | 8.6 | 9.6 |
| | $^{242}$Pu | 7.6 | 8.5 |
| | $^{241}$Am | 3.9 | 1.0 |
| | $^{242m}$Am | 0.1 | 0.0 |
| | $^{243}$Am | 1.3 | 0.0 |
| | $^{244}$Cm | 0.4 | 0.0 |
| | $^{245}$Cm | 0.0 | 0.0 |
| | Total | 100.0 | 100.0 |

At first, the effects of FPs or MAs have been investigated individually as the parameter effect study. On the effects of MAs, the evaluation conditions are determined to assume all MAs be contained in the fresh fuel and all FPs be removed from the spent fuel of a typical BWR core with the discharge burn-up of 45 GWd/t. The resultant TRU composition in the fresh fuel is listed in Table 2 in comparison with the standard fuel composition of our study. The total amount of MAs is 11 wt% of TRU. Especially in this case, the amount of $^{237}$Np is large due to production from $^{235}$U in the $UO_2$ core. Although $^{241}$Am is included in the standard case, this comes from decay of $^{241}$Pu.

In general, the main effect of MAs and FPs in the fuel is to reduce the criticality of the core due to their neutron absorption. In addition, MAs tend to have some effect on the void reactivity coefficient to make it positive. For the present MA effect case, the amount of fissile Pu is to be increased by about 10 % to keep the criticality. Also, MAs, especially $^{237}$Np, make the void reactivity coefficient to be positive. Therefore, we have to change the design to keep the void reactivity coefficient to be negative. In the present design, the void reactivity coefficient can be controlled mainly by the length of the upper blanket. If the upper blanket is shortened, the void reactivity coefficient becomes lower. However, it should be noted that this, in turn, makes the conversion ratio lower. For the present case, the upper blanket should be significantly shortened up to about 30 % of the standard case. The lengths of the lower and the internal blanket are simultaneously adjusted to 140 and 400 mm, respectively, to improve the core performances. As a result, the fissile Pu conversion ratio is reduced to 1.02. This result shows that the RMWR core can be feasible under the MA effect case fuel composition described above, although the effects of MAs are significant. The major dimensions and characteristics of the core are summarized in Table 3 in comparison with the standard case.

*Table 3 : Major core dimensions and characteristics for MA effect case*

| Item | | MA effect case | Standard case |
|---|---|---|---|
| Electric power output | (MWe) | 1,100 | 1,100 |
| Discharge burn-up for core part | (GWd/t) | 45 | 45 |
| Core height | (m) | 0.835 | 0.68 |
| Core mass flow rate | ($10^4$t/h) | 1.3 | 1.3 |
| Core exit quality | (%) | 54 | 55 |
| Core average void fraction | (%) | 70 | 70 |
| Core average fissile Pu content | (%) | 9.4 | 10.2 |
| Loaded fissile Pu | (t) | 13.8 | 12.1 |
| Fissile Pu conversion ratio | (−) | 1.02 | 1.06 |
| Maximum linear power density | (kW/m) | 55.8 | 55.8 |
| MCPR | − | 1.3 | 1.3 |
| Void reactivity coefficient | ($10^{-4}$ Δ k/k／%void) | -0.5 | -1 |
| Operation cycle length | (EFPM) | 14 | 14 |
| Core axial fissile Pu enrichment distribution | mm | DU 100 | DU 330 |
| | wt% mm | 18 210 | 18 185 |
| | mm | DU 400 | DU 295 |
| | wt% mm | 18 225 | 18 200 |
| | mm | DU 140 | DU 200 |
| Amount of MA/FP in MOX (wt%) | | 3.9 / 0 | 0 / 0 |

On the effects of FPs, the evaluation conditions are determined to assume a part of FPs be contained in the fresh fuel based on the concerned DFs and all MAs be removed from the spent fuel of a typical BWR core with the discharge burn-up of 45 GWd/t. Two sets of DFs are selected for the investigation, assuming an advanced PUREX reprocessing and a dry reprocessing scheme. Although the average value of DFs for the latter is much lower and about 10, the same fissile Pu conversion ratio of 1.06 has been attained under the negative void reactivity coefficient. In these cases, the fissile plutonium is also to be increased by about 10 % to keep the criticality.

For more realistic investigation on the multiple recycling situation, their effects have been investigated together as the accompanied FPs and MAs under the multiple recycling with the RMWR and an advanced reprocessing in relatively low DFs. The evaluation conditions are determined to assume all MAs and a part of FPs be contained in the fresh fuel. The average DF of 10 for FPs is adopted assuming a dry reprocessing case. The equilibrium for the recycling has been obtained after about 20 times recycling calculations. The resultant TRU composition in the fresh fuel is listed in Table 4 in comparison with the standard fuel composition. The total amount of MAs is 6 wt% of TRU. In this case, the amount of $^{237}$Np is much smaller than in the case of Table 2 due to the MOX core reprocessing. In table 4, some differences in Pu composition from the standard case are also observed. That is, the rate of $^{241}$Pu is decreased and $^{240}$Pu is increased in the multiple recycling case.

*Table 4 : TRU composition for multiple recycling case*

| Item | | Recycling case | Standard case |
|---|---|---|---|
| Conditions | Origin core | RMWR core | BWR core ($UO_2$) |
| | Discharge burn-up (GWd/t) | 45 | 45 |
| TRU Composition (wt%) | $^{237}$Np | 0.5 | 0.0 |
| | $^{238}$Pu | 2.4 | 2.7 |
| | $^{239}$Pu | 50.6 | 47.9 |
| | $^{240}$Pu | 34.0 | 30.3 |
| | $^{241}$Pu | 4.1 | 9.6 |
| | $^{242}$Pu | 3.2 | 8.5 |
| | $^{241}$Am | 3.6 | 1.0 |
| | $^{242m}$Am | 0.1 | 0.0 |
| | $^{243}$Am | 0.9 | 0.0 |
| | $^{244}$Cm | 0.5 | 0.0 |
| | $^{245}$Cm | 0.1 | 0.0 |
| | Total | 100.0 | 100.0 |

For the multiple recycling case, the amount of MAs and FPs contained in the MOX are 1.8 and 1.0 wt%, respectively. Also, the rate of $^{241}$Pu, which has good effect on criticality, is decreased. Therefore, fissile plutonium is to be increased by about 10 % to keep the criticality. On the void reactivity coefficient, there are about 2wt% of MAs contained in the MOX. In addition, the rate of $^{240}$Pu, which has the unfavorable effect on the void reactivity coefficient, is increased as mentioned above. Therefore, we have to change the design to keep the void reactivity coefficient to be negative. As in the MA effect study, we can make the void reactivity coefficient lower by mainly shortening the length of the upper blanket. For the present case, the upper blanket should be significantly shortened up to about 40 % of the standard case. The lengths of the lower and the internal blankets are simultaneously adjusted to 150 and 400 mm, respectively, to improve the conversion ratio and the void reactivity coefficient. As a result, the fissile Pu conversion ratio is reduced to 1.02. This result, however, shows that the RMWR core can be feasible under the multiple recycling fuel composition.The major dimensions and characteristics of the core are summarized in Table 5 in comparison with the standard case.

*Table 5 : Major core dimensions and characteristics for multiple recycling case*

| Item | | Recycling case | Standard case |
|---|---|---|---|
| Electric power output | (MWe) | 1,100 | 1,100 |
| Discharge burn-up for core part | (GWd/t) | 45 | 45 |
| Core height | (m) | 0.84 | 0.68 |
| Core mass flow rate | ($10^4$t/h) | 1.4 | 1.3 |
| Core exit quality | (%) | 51 | 55 |
| Core average void fraction | (%) | 68 | 70 |
| Core average fissile Pu content | (%) | 9.4 | 10.2 |
| Loaded fissile Pu | (t) | 13.7 | 12.1 |
| Fissile Pu conversion ratio | (—) | 1.02 | 1.06 |
| Maximum linear power density | (kW/m) | 52.5 | 55.8 |
| MCPR | — | 1.3 | 1.3 |
| Void reactivity coefficient | ($10^{-4}\Delta$k/k／%void) | -0.5 | -1 |
| Operation cycle length | (EFPM) | 14 | 14 |
| Core axial fissile Pu enrichment distribution | mm<br>wt% mm<br>mm<br>wt% mm<br>mm | DU 130<br>18 215<br>DU 400<br>18 225<br>DU 150 | DU 330<br>18 185<br>DU 295<br>18 200<br>DU 200 |
| Amount of MA/FP in MOX (wt%) | | 1.8 / 1.0 | 0 / 0 |

Based on these investigation, it has been confirmed that the high conversion ratio more than 1.0 and the negative void reactivity coefficient are able to be achieved in the RMWR core by slightly adjusting the basic core design, even under the multiple recycling through the advanced fuel reprocessing schemes with the lower DFs around 10 assumed for FBR fuel cycle. Through the study, the unfavorable effect of MAs on the void reactivity coefficient has been found to be significant. Therefore, in the Pu multiple recycling fuel cycle for the RMWR, a reprocessing scheme with higher DFs for MAs is considered to be favorable.

## 5- CONCLUSIONS

An advanced water-cooled reactor concept named the RMWR has been proposed. The RMWR aims at to attain a high conversion ratio more than 1.0 and to achieve the negative void reactivity coefficient, based on the well-experienced water reactor technology. At present, several types of design concepts satisfying both design targets have been proposed based on the evaluation for the MOX fuel obtained through the current PUREX reprocessing process with very high DFs. That is, the MOX fuel does not contain FPs and/or MAs.

However, for the RMWR utilization, the multiple recycling of Pu is the essential basis under the MOX spent fuel reprocessing fuel cycle as for FBRs. The advanced reprocessing schemes currently proposed for the FBR fuel cycle are in general with the low DFs, and hence, allows some amount of FPs and MAs to remain in MOX fuel. Since they are expected to have negative effects on the core performances and the conversion ratio of the RMWR is just more than 1.0, some investigation on the core performances of the RMWR under multiple recycling situation with such the advanced fuel reprocessing schemes in relatively low DFs.

Through this investigation, the unfavorable effect of MAs on the void reactivity coefficient has been found to be significant. Based on the investigation, it has been confirmed that the high conversion ratio more than 1.0 and the negative void reactivity coefficient are able to be achieved in the RMWR core by slightly adjusting the basic core design, even under the multiple recycling including the advanced fuel reprocessing schemes with the low DFs around 10 assumed for the FBR fuel cycle.

## REFERENCES

[1] - T. Okubo, *et al.*, “Conceptual Designing of Reduced-Moderation Water Reactors (1) – Design for BWR-type Reactors --”, Proc. ICONE 8, ICONE-8422 (2000).

[2] - K. Hibi, *et al.*, “Conceptual Designing of Reduced-Moderation Water Reactors (2) – Design for PWR-type Reactors --”, Proc. ICONE 8, ICONE-8423 (2000).

[3] - R. Takeda, *et al.*, “General Features of Resource-Renewable BWR (RBWR) and Scenario of Long Term Energy Supply”, Proc. GLOBAL ’95, 938 (1995).

[4] - J. Sugimoto, *et al.*, “Thermal-hydraulic Characteristics of Double Flat Core HCLWR”, JAERI-M 89-002 (1989).

[5] – H. Maruyama, *et al.*, “A Monte Carlo Method with Pseudo Scattering for Neutron Transport Analysis”, *Proceedings of International Topical Meeting on Advances in Reactor Physics, Mathematics and Computation*, Paris (1987).

[6] – T. Matsumoto, *et al.*, “Development of Critical Power Correlation for Tight Lattice Fuel Assembly”, *1987 Annual Meeting of Atomic Energy Society of Japan*, E40 (1987).

[7] – B.W. LeTourneau, *et al.*, “Critical Heat Flux and Pressure Drop Tests with Parallel Upflow of High Pressure Water in Bundles of Twenty 3/4-in. Rods”, *Nucl. Sci. Eng.*, **54**, 214 (1974).

[8] – T. Ikegami, *et al.*, “Feasibility Study on Reprocessing System for FBR”, [to be published as JNC TY9400 report].