ANNEX XXVI.

STUDIES OF MINOR ACTINIDES TRANSMUTATION IN SODIUM COOLED FAST REACTOR

XXVI-1. INTRODUCTION

XXVI-1.1. Background

Nuclear power brings issues to human society and environment while providing energy resource, where the safe disposal of long-lived high level waste (LHLW) is the most urgent issue and becomes one of the factors that restrict development of nuclear energy in many countries.

High level waste generated in nuclear power plant mainly refers to the discharged spent fuel or the high radioactive waste formed in the processing of spent fuel. Unlike other industrial waste, the non-hazardous disposal of radioactive waste is achieved only by nuclide decay. LHLW cannot be disposed in a non-hazardous way in a short term because of its long life characteristics. LHLW consists of minor actinides (MA) and long-lived fission products (LLFP).

The Partitioning and Transmutation (P&T) strategy can be utilized to dispose LHLW. In P&T, the long-lived MA and LLFP are separated from high level waste and then transmuted in reactors to become stable or relatively short-lived nuclides. Sodium cooled fast reactor (SFR) is currently realistic and effective transmutation device.

In this Annex, the strategy of MA transmutation in SFR was studied in two different ways. The first one is putting transuranics (TRU) from PWR spent fuel into SFR as fuel, and the TRU will then be multi-recycled to transmute MA contained; the other way is using specially designed burner SFR to transmute MA separated from PWR spent fuel. The peculiarities of the two ways are studied and compared in this study.

XXVI-1.2. Description of SFR core

The conceptual design of 800 MW(e) SFR with thermal power of 2100 MW is used as reference reactor core, which is designed by the China Institute of Atomic Energy [XXVI-1 and XXVI-2]. The reactor core is similar to the Russian BN-800 plant, except for an additional radial blanket row and extended cycle time from 140 days to 160 days. General parameters of in-core subassemblies such as fuel subassemblies, control rods, reflector and shielding subassemblies are the same as those of BN-800 core.

In the core MOX fuel is used, in which heavy metal (HM) is composed of depleted uranium and industrial Pu from PWR spent fuel with burn-up ratio of 45 GWday/tU. The isotopic composition of plutonium is $^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$=0.009/0.615/0.220/0.119/0.041 (%weight).

A 1/3 core refuelling scheme is adopted, which means fuel subassemblies will stay in the core for 3 cycles with total irradiation time of 480 days. The average fuel discharge burn-up is 73.5 GWday/tHM, with the maximum burn-up of 111.4 GWday/tHM. The blanket subassemblies will stay for 4 cycles or 640 days.

The core configuration and main design parameters are presented in Fig. XXVI-1 and Table XXVI-1, respectively.

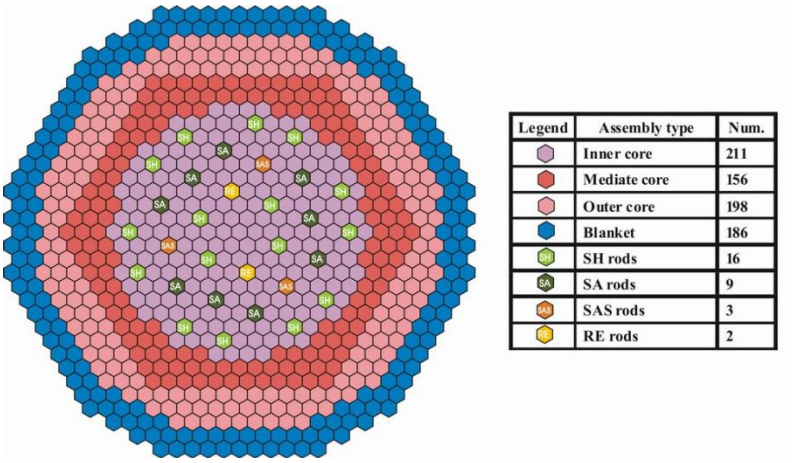

FIG. XXVI-1. Core configuration of the reference core.

TABLE XXVI-1. MAIN DESIGN PARAMETERS OF REFERENCE CORE

Parameters	Value
Power, MW	
Thermal	2100
Electric	800
Fuel type	MOX (PuO_2-dep.UO_2)
Fissile materials fraction(1), %weight	
Inner zone	19.5
Middle zone	22.1
Outer zone	24.7
Volume fraction, %	
Sodium (Na)	39.3
Stainless steel	21.9
Fuel	33.2
Gap	5.6
Core dimension, cm	Eq. D 249.6×H 88.0 (20°C)
Core initial loading, kg	
^{235}U	29.7
Total U	9887.2
^{239}Pu +^{241}Pu	1998.9
Total Pu	2757.1

(1): (^{235}U+Pu) mass/HM mass

XXVI-1.3. Computational tools

Computational tools were divided into two categories, one is for criticality calculation, including the CITATION code [XXVI-3] and the PASC-1 code [XXVI-4] which generates the few-group library for CITATION code; the other is for isotopic burn-up calculation, in which ORIGEN code [XXVI-5] is used to analyze the composition change of TRU when it is multi-recycled.

The fine 171 groups NVitamin-C library was used as the source library. This library is an updated version of the Vitamin-C library and developed by the Nuclear Data Center of

CIAE (China Institute of Atomic Energy), based on the evaluated nuclear data libraries ENDF/B-VI, JEF-2, CENDL-2 and JENDL-3. Compared with the Vitamin-C library, the new library contains more nuclides (105 instead of 66, two of them are pseudo fission products of ^{235}U and ^{239}Pu, respectively) and is processed by newer evaluation library [XXVI-6].

Full core 3D diffusion calculation, including steady state, burn-up and perturbation calculation, is performed by the CITATION code, which is widely used in reactor core neutronics analysis and has proved to be reliable.

The few group microscopic cross section library prepared for CITATION code is generated by PASC-1 code system for the specific core layout geometry. The CITATION-used cross section library can be processed in a variety of ways, but XSDRN code [XXVI-7], 1D SN transport code in PASC-1, is specifically designed for this purpose. PASC-1 code system is a code package for condensing multi-group cross sections into few groups and is similar to AMPX. The flow chart of the process is presented in Fig. XXVI-2 [XXVI-8].

Finally, the equilibrium composition analysis of TRU and some other associated parameters of TRU multi-recycling, such as TRU radioactivity and thermal power, is performed with the help of the ORIGEN code, which had been developed for isotopic burn-up and decay analysis in nuclear fuel cycle process. It should be noted that single-group cross sections used in ORIGEN code (i.e., 302 lib in ORIGEN) are updated with the actual neutron spectrum of reference core, which means that the reference core neutron spectrum is used to condense a new 302 lib for the ORIGEN code.

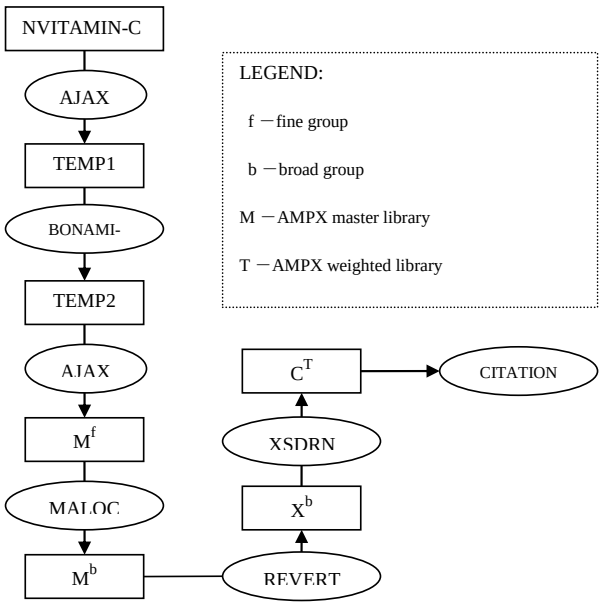

FIG. XXVI-2. Flow chart showing generation of a few-group microscopic cross section library.

XXVI-2. INTEGRATED TRU MULTI-RECYCLING IN REFERENCE CORE

Reference core driver fuel was changed from pure Pu to integrated TRU from PWR spent fuel, and then the impacts on core performance were analyzed. TRU composition refers to PWR Daya Bay reactor spent fuel with burn-up of 45.0 GWday/t and cooling time of 3 years (weight percentage: MA/Pu =10.1/89.9 [XXVI-9]). Other parameters, like Pu fraction in HM in initial core, core thermal power and cycle length are kept unchanged. The differences between core initial loading for two cores are given in Table XXVI-2. Compared with the

standard core, in the initial state of TRU fuelled core the MA loading mass increases from 0 to ~310.3 kg and the U loading mass decreases by about 310.1 kg, while Pu loading mass remains unchanged.

TABLE XXVI-2. INITIAL CORE LOADING

	Reference core	Reference core fuelled with TRU
Fuel composition	(Pu, U) O_2	(TRU, U)O_2
Initial core loading, kg		
U	9887.2	9577.1
Pu	2757.1	2757.1
MA	0	310.3

XXVI-2.1. Impacts on certain core safety parameters associated with neutronics

Theoretical calculations and analyses show that certain amount of MA addition to sodium cooled fast reactor fuel will have certain impact on core performance, mainly on safety and kinetic parameters including the reduced fuel Doppler feedback, the increased sodium void worth, the decreased burn-up reactivity loss ($\Delta\rho_{burn\text{-}up}$) and core effective delayed neutron fraction (β_{eff}) [XXVI-10 and XXVI-11]. However, except for the sodium void worth, these impacts could be negligible for the core with the lower MA weight percentage in TRU. As the calculation results show (Table XXVI-3), in comparison with the reference core β_{eff} and $\Delta\rho_{burn\text{-}up}$ decrease by 2.6% and 13.0% respectively, Doppler constant is reduced numerically by 16.0%, while sodium void worth, which is positive, increases by 45.0%. On the other hand, the maximum power density, the location of subassembly with maximum power density and the maximum and average fuel burn-up are almost not changed. Regarding core neutron flux, the maximum flux decreases slightly, but the location of the maximum flux subassembly is the same as in the reference core.

TABLE XXVI-3. COMPARISON OF SAFETY AND KINETIC PARAMETERS AT BEGINNING OF CYCLE (BOC) IN EQUILIBRIUM STATE

	β_{eff} /pcm[1]	$\Delta\rho_{burn\text{-}up}$ /$	K_D (1) /pcm	Sodium void worth (2) /$
Reference core	381.845	9.467	-792.995	2.254
Reference core fuelled with TRU	372.015	8.239	-666.426	3.269

(1): Doppler constant, which is used to evaluate Doppler feedback reactivity when fuel average temperature increases from *T1* to *T2*: $\Delta\rho = K_D \ln \frac{T2}{T1}$.

(2): Assumed that sodium voiding is only in core zone.

[1] pcm is *per cent mille*, one-thousandth of a percent.

Among these parameters, the one most significantly changed is the sodium void worth. This value represents reactivity worth introduced by Na void or loss of Na and is an important parameter connected to reactor safety. Na void will mainly bring on three phenomena, including neutron spectrum hardening (Fig. XXVI-3), increase in neutron leakage and decrease in Na capture, where the first two effects dominate Na void reactivity feedback. In sodium cooled fast reactor, the hardening of neutron spectrum causes positive reactivity, while the increased leakage causes negative reactivity. Particularly in large core, the reactivity change caused by neutron spectrum hardening is much larger than that caused by the increased leakage. Meanwhile, for main nuclides (like ^{237}Np and ^{241}Am), their fission capability is very sensitive to incident neutron energy in the energy range of 0.1-1MeV, as shown in Fig. XXVI-4 which presents the average number of neutrons produced per neutron absorption (η value) for different nuclides. In other words, once core neutron spectrum is hardened, the reactivity worth of MA nuclides would be increased significantly. Therefore, in case of loading integrated TRU as reactor fuel, Na void worth will be increased significantly because a certain amount of MA is introduced into fuel.

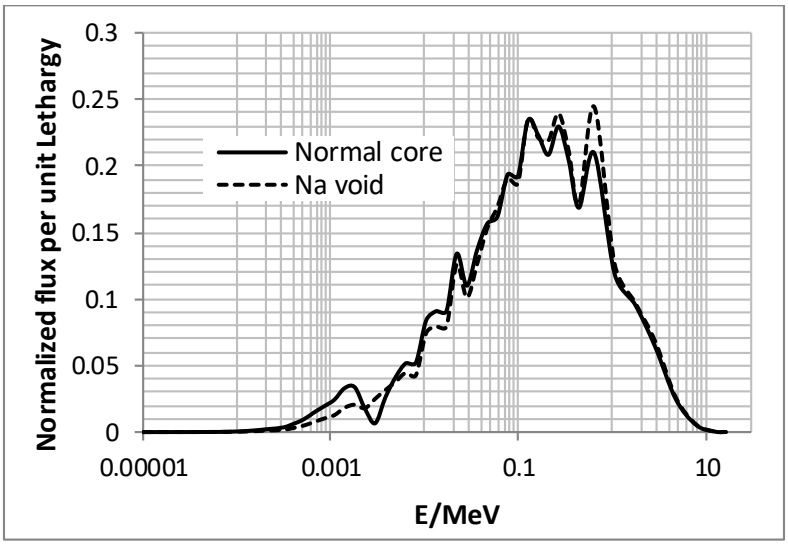

FIG. XXVI-3. Neutron spectrum for Na void and normal core.

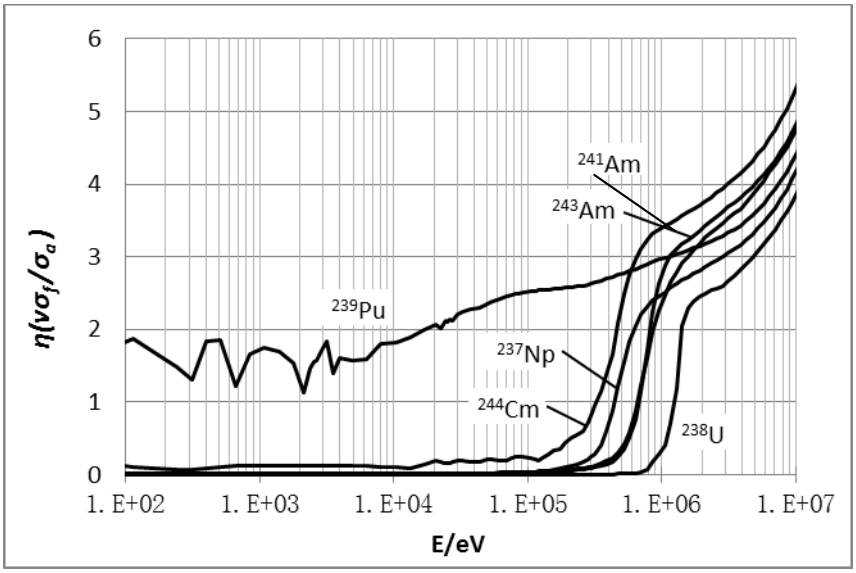

FIG. XXVI-4. η value for different nuclides in the energy range of 100eV-10MeV (data from NVitamin-C lib).

In the reference core design, in order to reduce the core sodium void worth only the lower blanket at the bottom of core is used, and the upper blanket is replaced by a sodium cavity to increase axial neutron leakage. Such configuration can successfully reduce Na void worth to about -0.6$[2] when Na in the core and the core upper region both void. That means, if the liquid sodium in the core and upper sodium cavity starts boiling, a negative reactivity of ~-0.6$ will be introduced. Even in TRU fuelled core, considering the same situation, Na void worth has only a slightly positive value (about 0.5$), which indicates the core is still safe enough. According to the actual engineering experience, 5$ seems to be a reasonable sodium void worth in large core (Na voiding only in core zone), since some engineering measures are always used to cope with the positive feedback to make the core safe.

XXVI-2.2. Impacts on core breeding performance

As shown in Table XXVI-4, the whole core breeding ratio for equilibrium core decreases slightly in TRU fuelled core, namely, from 1.046 in the reference core to 1.030 in TRU core. In fact, the conversion ratio in the core zone is reduced by about 2.5%, but there is no obvious change in the blanket zone. Therefore, if TRU is used to replace pure Pu as driver fuel in sodium cooled fast breeder, the utilization of U resources can still be improved.

As far as Pu consumption is concerned, the overall consumption rate of Pu in TRU fuelled core is 10.5% less than that in standard core, which is mainly caused by the accumulation of converted MA in ^{238}Pu. Thus, if one compares consumption of fissile Pu isotopes (^{239}Pu+^{241}Pu), the rate in TRU fuelled core is 1.5% higher than that in a standard core. In the recycled TRU core, ^{238}Pu fraction in Pu in spent fuel is about 4 times higher than that in a standard core, due to the effect of MA conversion.

TABLE XXVI-4. COMPARISON OF BREEDING PERFORMANCE FOR THE CORE WITH TWO FUEL TYPES (IN EQUILIBRIUM)

	BR(1)	Core Pu mass/kg			Core $^{(239+241)}$Pu mass/kg		
		BOC	EOC	$\Delta_{EOC-BOC}$	BOC	EOC	$\Delta_{EOC-BOC}$
Reference core	1.046	2633.6	2523.6	-110.0	1864.8	1745.5	-119.3
Reference core fuelled with TRU	1.030	2646.3	2547.9	-98.4	1861.6	1740.5	-121.1

(1) : Breeding ratio for equilibrium core.

XXVI-2.3. Comparison of MA transmutation effects

MA and TRU transmutation characteristics in reference core and the TRU fuelled reference core are compared in Table XXVI-5. The results show that between two cores the most significant difference is in the MA transmutation effect. In the reference core with no MA in initial loading the MA inventory in fuel increases gradually with a rate of about 8.8 kg/cycle, equivalent to 24.7 kg/GW(e)year, which is even 23.5% higher than MA generation rate in UO_2 fuelled PWR core (~20 kg/GW(e)year). In TRU fuelled core, however, since the

2 The value is different from the one in Table XXVI-3, because in Table XXVI-3 the assumption of Na voiding is made only for the core zone.

initial fuel loading contains a certain amount of MA, the MA will be transmuted effectively. If TRU is recycled many times, the MA percentage in TRU will decrease gradually until the equilibrium state (MA equilibrium composition with TRU multi-recycling will be discussed in Section 4 of this Annex). In the first TRU recycle core, the MA transmutation rate is 21.8 kg/cycle, equivalent to ~61.3 kg/GW(e)year.

From a TRU transmutation point of view, there is no essential difference between the two cores. In a TRU fuelled core, as there is slightly reduced breeding ratio and considerable transmutation of MA, the TRU consumption is 18.8% higher than that in the reference core, which is shown in detail in Table XXVI-5.

TABLE XXVI-5. COMPARISON OF MA AND TRU TRANSMUTATION EFFECT

	MA initial loading, *kg*	Transmutation mass[(1)] *kg*		Specific consumption *kg/GW(e)year*	
		ΔM_{MA}	ΔM_{TRU}	MA	TRU
Reference core	0	-8.8	101.2	-24.7	284.6
Reference core fuelled with TRU[(2)]	310.3	21.8	120.2	61.3	338.1

[(1)]: This value means MA or TRU transmutation mass within 1 cycle of equilibrium core, only in the core zone without blanket, and negative value means MA mass increases with fuel burn-up.

[(2)]: This is the first TRU recycle core.

XXVI-2.4. TRU composition change with TRU multi-recycling

XXVI-2.4.1. Calculation method

When TRU is loaded as driver fuel and multi-recycled in the reference core, the composition of TRU will change gradually. This section studies the changing rules of TRU composition and the issues associated with TRU multi-recycling. In addition, as a supplement to MOX fuel, the above-mentioned characteristics are also compared to the case when TRU recycled in metal fuel core.

In order to be consistent with the reference core, the new updated one-group actinides' cross section library (lib) for ORIGEN code was used to substitute for the original 302 lib. The neutron spectrum is considerably different (Fig. XXVI-5) between MOX fuel core and metal fuel core, and the one-group cross section lib is processed with the corresponding spectrum respectively. The neutron spectrum for the two fuel types in Fig. XXVI-5 was obtained by Monte Carlo code MCNP.

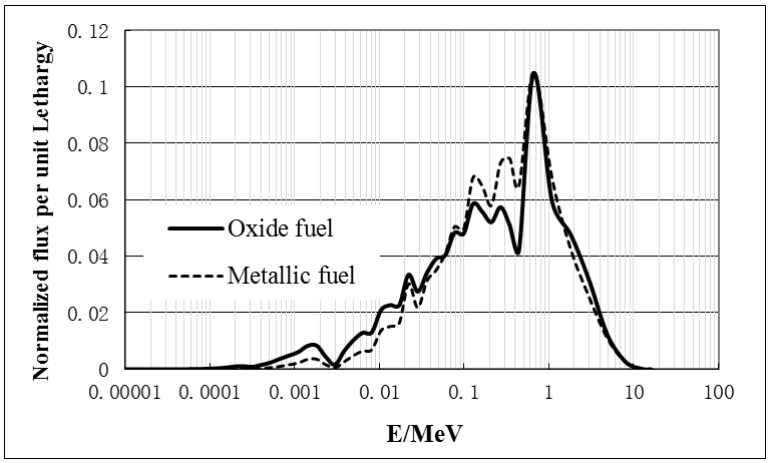

FIG. XXVI-5. Neutron spectrum of different fuel types.

When using ORIGEN code for fuel burn-up calculation, the method of keeping the specific power of fuel irradiation is used, and by adjusting the irradiation time, the fuel is irradiated to a burn-up of ~70 MWday/kg in one cycle. This burn-up is the average value for standard MOX reference core spent fuel, and the same fuel burn-up was chosen for metal fuel. After one irradiation cycle, it was assumed that the spent fuel with 1 year of cooling will be reprocessed to recover TRU and then new fuel will be fabricated. When creating new fuels virtually, TRU is blended with depleted uranium and the composition of TRU is kept unchanged from the recovered TRU, and then the ratio of TRU and U is adjusted to 0.320 and 0.202 for MOX fuel and metal fuel, respectively. The ratios of 0.320 and 0.202 were chosen because they are the average TRU and U ratio of the initial fuel load in a standard MOX fuelled reference core and metal fuelled core, respectively.

XXVI-2.4.2. Change of TRU composition

When TRU is multi-recycled, the characteristics of TRU composition are different for the two fuel types, as shown in Fig. XXVI-6 for MA and Pu weight percentage, and in Fig. XXVI-7 for the weight percentage of different MA elements (Np, Am and Cm) in TRU. In Figures XXVI-6 and XXVI-7 the vertical axis represents weight percentage and the horizontal axis represents the total number of TRU recycles. As mentioned above, for each cycle the fuel was irradiated to a burn-up of 70 MWday/kg.

Regarding MA weight percentage (on the premise of keeping fixed ratio of TRU and U in HM when TRU is recycled), the results of Fig. XXVI-6 indicate that the MA fraction decreases more rapidly in metal fuel, and is also lower than that in MOX fuel. If TRU is recycled in reference core (MOX fuel), the MA percentage in TRU will first decrease to ~7.24% (minimum) within 8 TRU recycle periods and then slowly increase to ~7.7% after 20 TRU recycle periods. The increase of MA fraction may be caused mainly by Cm accumulation in MOX fuel. However, in the case of metal fuel, the equilibrium state for MA fraction will be achieved after ~15 TRU recycles, and the equilibrium percentage is about 3.8%. Once the equilibrium state in metal fuel is realized, the MA percentage in TRU will be stable and considerably lower than the MA percentage in PWR spent fuel. This means the MA inventory is effectively controlled. Such performance demonstrates a better MA transmutation effect for metal fuel compared to MOX fuel.

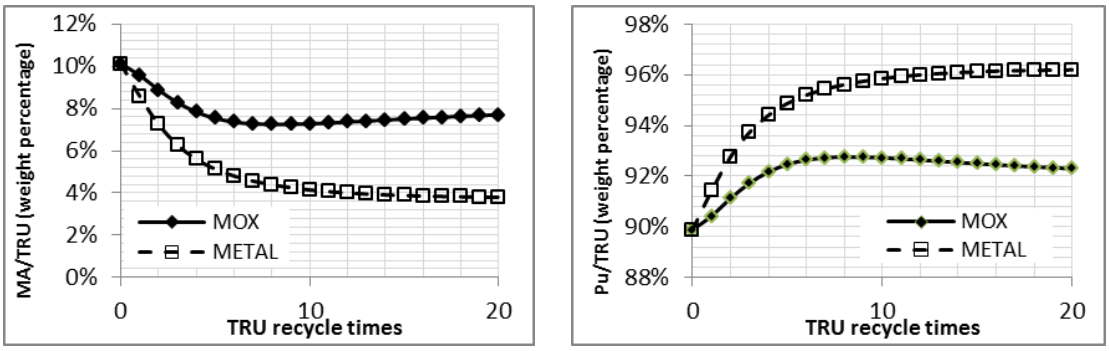

FIG. XXVI-6. MA and Pu percentage in TRU when TRU is multi-recycled.

In terms of MA element composition (Fig. XXVI-7), when TRU is multi-recycled, the Np equilibrium percentage in TRU is similar for two fuel types, while for Am and Cm the situation is different. When using metal fuel, the Am and Cm weight percentage is considerably lower than in MOX fuel. Especially for Cm (a high atomic number element with high heat and neutron emission), the percentage increases at first and then decreases gradually after the TRU has been recycled for 7 periods in metal fuel core, while in MOX fuel core Cm percentage increases continuously and cannot achieve equilibrium state even in case of 20 TRU recycle periods. It could be noted that, if TRU is recycled many times, Am and Cm fractions in TRU in MOX fuel will be much higher than those in metal fuel. For example, after TRU has been recycled for 10 periods, the Am fraction in TRU is ~3.9% for MOX fuel and ~2.3% for metal fuel, while Cm fraction is about 2.8% for MOX fuel (still increasing) and 1.3% for metal fuel (starting to decrease slowly). This difference is mainly due to neutron spectrum in metal fuelled core being harder than that in MOX fuelled core. For main MA nuclides, harder neutron spectrum will always bring larger ratio of fission/capture cross sections, which means there is a greater chance of a fission reaction and smaller chance of a capture reaction, and that leads to a smaller production of Am and Cm in metal fuel.

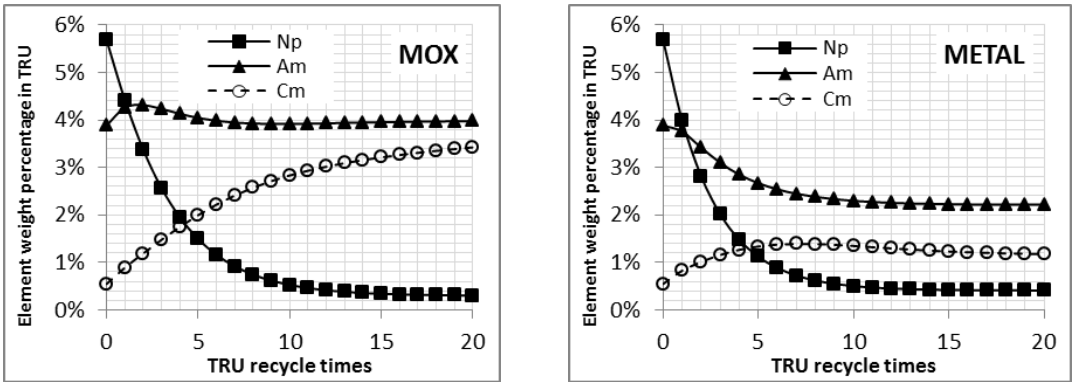

FIG. XXVI-7. Element weight percentage in TRU when TRU is multi-recycled.

In addition, whether in MOX fuel or metal fuel, after TRU has been recycled for 5-6 cycles, the equilibrium state of Pu composition will be achieved, as shown in Fig. XXVI-9 showing the change of Pu isotopic composition in the case of multi-recycling. In Fig. XXVI-9, the abbreviations "N" and "NF" mean fissile (^{239}Pu +^{241}Pu) and non-fissile (^{238}Pu +^{240}Pu+^{242}Pu) Pu isotopes respectively. For different fuel types, however, the equilibrium percentage of fissile Pu isotopes is different. It is known that due to high mass density (high atomic density for heavy metal nuclides) and hard neutron spectrum, the conversion effect of ^{238}U to ^{239}Pu in metal fuel core is higher than that in MOX fuelled core. Therefore, for metal

fuel the equilibrium fraction of ^{239} Pu +^{241}Pu in Pu is about 64%, while for MOX fuel a smaller fraction about 54% is obtained.

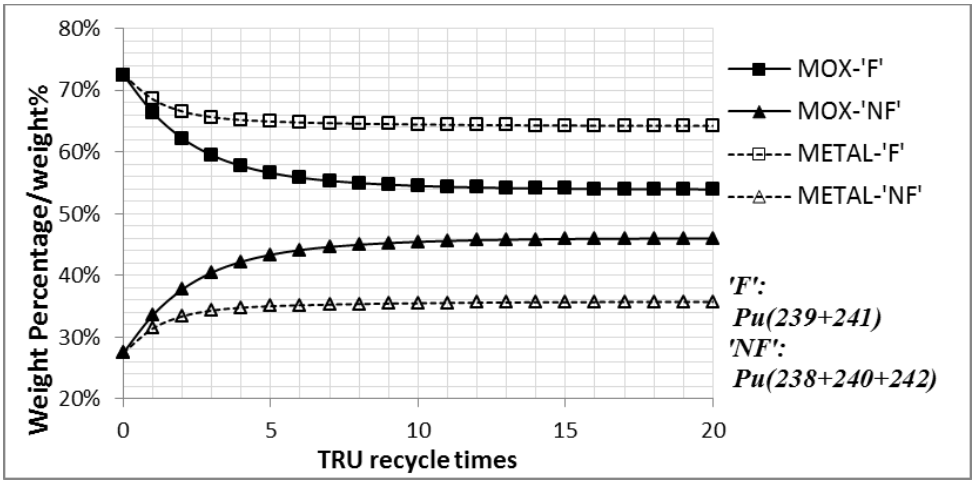

FIG. XXVI-8. Pu composition change when TRU is multi-recycled.

XXVI-3. MA BURNER REACTOR

In commercial power reactor, MA addition to fuel will introduce certain hazards to safe and stable operation of the reactor core; thus, it is better to separate commercial power generation and LHLW transmutation, which means designing special burner reactor dedicated to MA and LLFP transmutation and power generation at the same time. Dedicated burner reactor is based on the concept of double-strata fuel cycle proposed initially by Japanese researchers, in which MA and LLFP P&T fuel cycle is totally separated from commercial fuel cycle. The first stratum consists of standard power reactors, fuel fabrication and processing plants for commercial power generation; in the second level, MA and LLFP exist in high activity liquid waste from the first stratum and are separated and introduced into the fuel or target, and then irradiated in the dedicated burner reactors with fuel processing to realize multi-recycling [XXVI-12, XXVI-13 and XXVI-14]. European research shows that dedicated burner reactors in the second stratum, accounting for 5-20% in the whole nuclear energy system, could meet the requirement of MA transmutation [XXVI-15].

As the quantity of MA and LLFP required to be dealt with in the second stratum is relatively smaller than the quantity of spent fuel in the first stratum, the scale of the second stratum is smaller and is also beneficial in terms of overall optimization of fuel fabrication, reactor core design and fuel processing. Thus, a possible impact on the commercial fuel cycle associated with strong radiation, high decay heat of fuel and degradation of core safety is avoided. Meanwhile, P&T cycle is compact and can be arranged with all the facilities on a relatively short distance, which can help avoid problems caused by transportation of dangerous radioactive material and, therefore, is preferred for waste management.

In the two-strata cycle concept, one of the key elements is the dedicated MA burner device in the second stratum. The MA burner may be critical reactor or sub-critical ADS with homogenous or heterogeneous transmutation mode. Sufficient experience has been accumulated in design and operation of critical reactors with relatively mature technology, while in case of ADS systems there is presently no engineering practice, and the economic feasibility and stable operation ability of ADSs are yet to be confirmed. Therefore, dedicated critical fast reactor with associated closed fuel cycle is still an important choice for MA transmutation.

XXVI-3.1. MA burner design objective

Internationally, many countries have conducted design studies of dedicated MA burner fast reactors. JAERI in Japan has designed two MA burners, P-ABR and M-ABR [XXVI-14 and XXVI-16]. P-ABR uses nitride coated particle fuel and He coolant, and M-ABR uses metal fuel. The MA fraction in heavy metal (HM) is relatively high in these two reactors, reaching 64% and 65% respectively. U.S. researchers have also designed a MA burner reactor core MABR [XXVI-17, XXVI-18 and XXVI-19], using TRU-0.6Zr-0.04Tc metal as fuel and lead or lead-bismuth alloy as coolant. For MABR fuel, the MA percentage in HM is also high, reaching 52%. The common feature of the Japanese design of P-ABR and M-ABR, and the U.S. designed MABR is high percentage of MA in HM fuel in order to achieve high MA fission fraction and later high MA incineration consumption. However, all of them share the degradation of core safety parameters; i.e. β_{eff} in P-ABR and M-ABR is only 0.0026 and Doppler feedback is small indeed, whereas in MABR β_{eff} is only 0.0024 and fuel Doppler feedback almost amounts to zero (Doppler constant K_D is only -35pcm). Moreover, in order to achieve such small value of β_{eff} and Doppler feedback and to reduce positive sodium void reactivity, several unconventional ways have been used in the above-mentioned burner reactor, for example, P-ABR and M-ABR use up to 90% enriched Uranium as drive fuel, while the fuel sub-assembly(SA) of MABR is designed with a central cavity to increase neutron leakage and to reduce sodium void reactivity, and 4% of Tc is added into fuel to enhance negative Doppler feedback. In the present study, MA burner reactor objective with relatively conventional fuel composition and fuel sub-assembly structure is identified.

MA burner reactor focuses on MA transmutation, especially MA incineration, thus MA fission fraction in MA burner must account for a certain percentage, which is different for the commercial power reactors. But based on current research it is known that once the MA fission fraction is increased, the safety parameters will degrade and cause safety problems. In this report, the design objective of MA burning support ratio for MA burner is set to be more than 6, which means the mass of MA burned (fissioned) in burner reactor is more than in 6 PWR reactors with the same power level. According to the fact that MA burning support ratio is proportional to whole core MA fission fraction, in case of MA fission fraction conversion more than 10% of whole core MA fission fraction is hoped to achieve.

Considering preliminarily safety parameter limits, the design objective for MA burner reactor core is set as oxide fuel, with conventional fuel sub-assembly structure and fuel composition, linear power density lower than 48kW/m, sodium void reactivity lower than +5$ and whole core MA fission fraction larger than 10% (supporting ratio of MA incineration of more than 6).

XXVI-3.2. Overview of MA burner

According to the design objective of MA burner, at least 10% of MA fission fraction should be achieved. And as far as it is known, after MA fission fraction increase the core parameters will degrade inevitably, particularly the significantly increased positive sodium void reactivity. Geometry size reduction of burner reactor core appears to be feasible and effective method to overcome this problem. Therefore, MA burner is generally designed to be medium or small sized reactor, and the power level of MA burner in this report is set between 1300~1000 MW(th). Meanwhile, annular core design is studied to increase neutron leakage.

In comparison with the reference core described in Section 1.2 of this Annex, a sodium cavity is still set above core active zone, but the lower blanket is replaced by reflector and there is radial blanket sub-assembly. The core layout is designed in two parts, traditional cylindrical core and annular core, as shown in Figures XXVI-9 and XXVI-10. Figure XXVI-11 gives fuel sub-assembly axial layout. The height of active fuel zone is 72.82 cm, and there

are three fuel enrichment zones (inner, middle and outer fuel zone). The refuelling time remains 160d and Pu percentage in fuel is adjusted to ensure enough backup reactivity.

For core layout, four different cases were studied and the neutronics properties were compared:

- Case C1, traditional cylindrical core with 20weight% MA addition in three fuel zones;
- Case C2, traditional cylindrical core with 20weight% MA addition in middle and outer fuel zones, but no MA addition in inner fuel zone with high sodium reactivity worth, so as to reduce sodium void reactivity and to enhance Doppler feedback in inner fuel zone. Meanwhile, absorber layer is set under active zone to increase axial leakage and then reduce sodium void reactivity;
- Case C3, annular core with 20weight% MA addition in three fuel zones;
- Case C4, annular core with 20weight% MA addition in inner and outer fuel zones, but no MA addition in middle fuel zone with high sodium reactivity worth, so as to reduce sodium void reactivity and to enhance Doppler feedback in middle fuel zone.

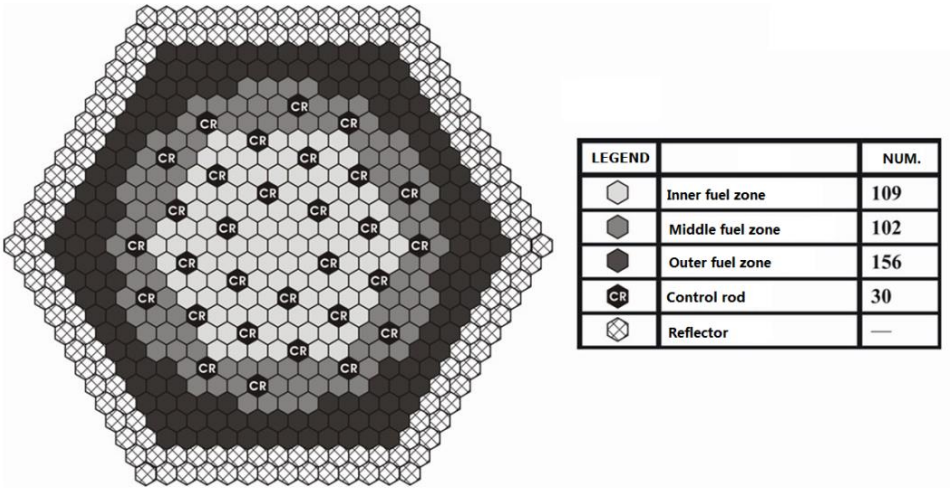

FIG. *XXVI-9. MA burner reactor core layout (traditional core).*

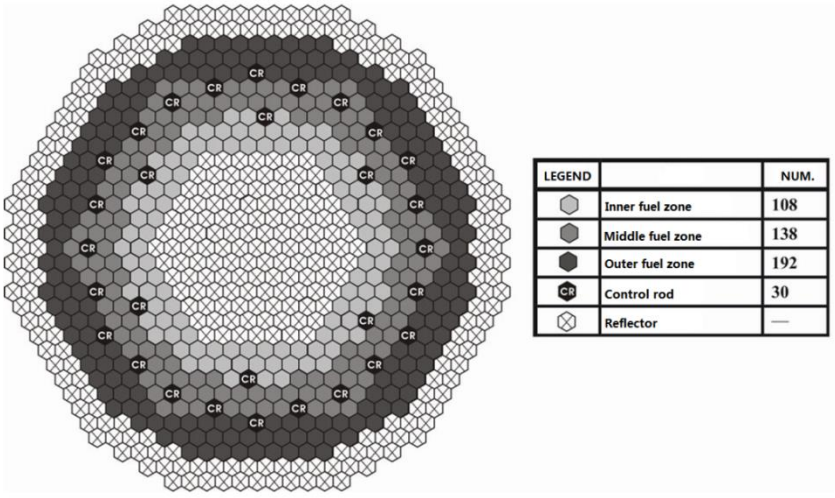

FIG. *XXVI-10. MA burner reactor core layout (annular core).*

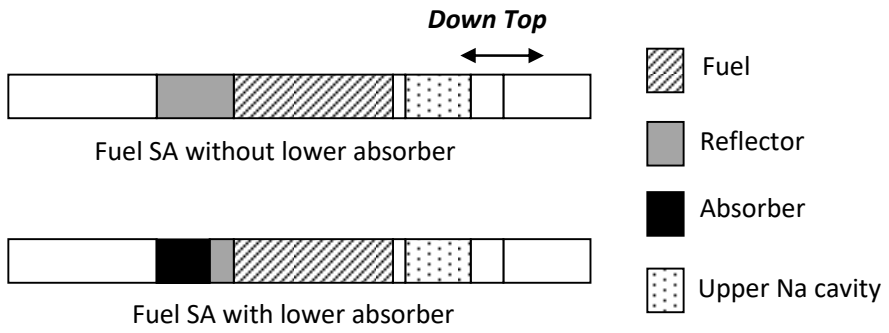

FIG. *XXVI-11. Axial layout of fuel sub-assemblies (SA).*

For C1~C4 corea, the PuO_2 percentage in fuel and HM mass load are presented in Table XXVI-6. As expected, along with neutron leakage increase, the specific loading mass of fissile material (fissile material loading mass corresponding to unit core thermal power; fissile material refers to ^{235}U plus Pu) is increased gradually, which means decreased neutron economy, but the largest gain in strong neutron leakage to reduce sodium void reactivity. The specific parameters are compared in the following section.

TABLE XXVI-6. HM LOADING IN DIFFERENT CASES

	C1	C2	C3	C4
Power level/ MW(th)	1120	1000	1300	1240
PuO_2 percentage/weight% (inner, middle and outer zone)	21.8/24.7/27.6	23.8/25.6/28.9	27.4/25.3/29.4	25.7/28.7/29.7
HM loading/kg：				
U	3692.5	3998.8	4205.7	4572.8
Pu	1669.8	1761.6	2194.2	2211.9
MA	1340.7	942.6	1600.1	1096.0
Fissile material specific loading mass, kg/MW(th)	1.501	1.774	1.698	1.795

XXVI-3.3. Comparison of key core parameters

For C1~C4 cores, the maximum linear power density and the maximum neutron flux are shown in Table XXVI-7, and core safety parameters are compared in Table XXVI-8.

In C1 and C3 core, because of all three fuel zones containing 20weight% MA, the whole core MA fission fraction is very high, reaching 19.6% and 18.3% respectively. However, as mentioned above, high MA fission fraction causes certain problems, such as β_{eff} decrease to less than 300 pcm, 297.1 pcm and 295.9 pcm respectively in C1 and C3 core, and a weak negative Doppler feedback with Doppler constant K_D only reaching -105.8 pcm and -124.9 pcm respectively, while sodium void reactivity increases significantly, reaching +8.2$ and +6.1$, respectively.

TABLE XXVI-7. MAXIMUM LINEAR POWER DENSITY AND MAXIMUM NEUTRON FLUX IN C1-C4 CORES

	C1	C2	C3	C4
Maximum linear power density, kW/m	46.3	44.1	47.0	46.0
Maximum neutron flux, $10^{15}/cm^2 \cdot s$	7.4	7.3	6.2	6.5

In C2 and C4 cores, as there is no added MA in the inner fuel zone (C2 core) and the middle fuel zone (C4 core), due to high sodium reactivity values and the placing of a neutron absorber layer under the active core zone in C2 core to increase axial neutron leakage – the sodium void reactivity is greatly reduced to +3.9$ in C2 core and to +3.0$ in C4 core, both less than the design objective of less than +5$. It should be reminded that in the reference core (standard design mentioned in Section XXVI-1.1.2) the sodium void reactivity is +2.3$ and +4.3$ after an addition of 5 weight% MA in the fuel. On the other hand, compared to C1 and C3 cores, since MA loading mass is reduced, the whole core MA fission fraction is decreased to 12.5% and 11.9% respectively for C2 and C4 cores, but both achieve the design objective of it being larger than 10%. In addition, the burn-up reactivity loss of C2 and C4 cores is increased to 9.9$ and 11.5$ respectively, compared to 9.5$ in the reference core; the Doppler feedback is also reduced, reaching only about 30% of the reference core, K_D being -240.1 pcm and -241.8 pcm, respectively.

TABLE XXVI-8. KEY PARAMETERS FOR DIFFERENT CORES

	Reference core	Reference core with 5 weight% MA in fuel	C1	C2	C3	C4
MA fission fraction, %	—	5.5	19.6	12.5	18.3	11.9
β_{eff}, pcm	381.8	369.3	297.1	323.0	295.9	320.3
$\Delta\rho_{burn\text{-}up}$, $	9.5	7.4	8.1	9.9	9.4	11.5
Na void reactivity, $	2.3	4.3	8.2	3.9	6.1	3.0
K_D, pcm	-793.0	-538.7	-105.8	-240.1	-124.9	-241.8
Conversion ratio	1.046	0.992	0.465	0.483	0.401	0.439

The fissile nuclide conversion ratio in C1~C4 cores is reduced significantly to a value between 0.4 and 0.5 due to the absence of a blanket zone and high MA percentage in fuel. As C1~C4 cores are designed to be MA burners, the lower conversion ratio accords with the design objective.

In C1 and C2 cores, the radial and axial distribution of sodium reactivity worth is shown in Figures XXVI-12 and XXVI-13, and the Doppler feedback for different fuel zones is shown in Fig. XXVI-14. Figure XXVI-15 shows radial distribution of sodium reactivity and Fig. XXVI-16 shows Doppler feedback distribution by fuel zones in C3 and C4 cores. The results from Figures XXVI-12, XXVI-13 and XXVI-15 indicate that MA exclusion from the zone with larger sodium reactivity can reduce the corresponding sodium void reactivity greatly, while introducing axial lower absorber zone can effectively increase axial leakage and realize considerable negative feedback compared to upper sodium cavity, thereby reducing sodium void reactivity. Meanwhile, as seen from Figures XXVI-14 and XXVI-16, the

Doppler feedback is enhanced in the fuel zone without MA addition, but other zones do not change considerably.

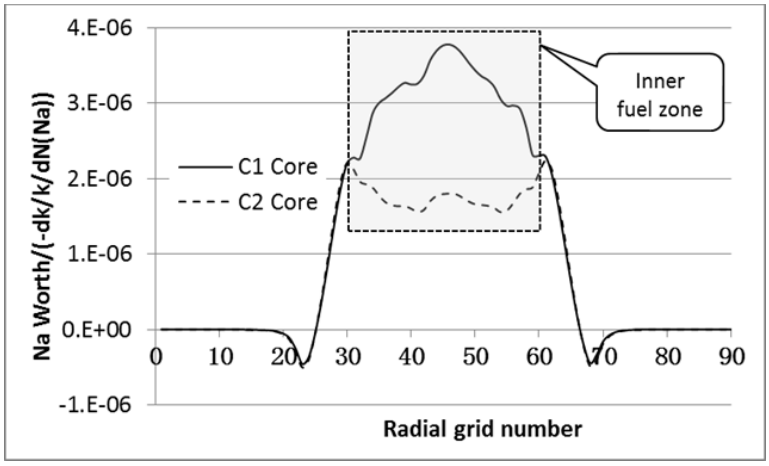

FIG. XXVI-12. Radial distribution of sodium reactivity worth in C1 and C2 cores (in central row on central plane, the abscissa is grid number in calculation).

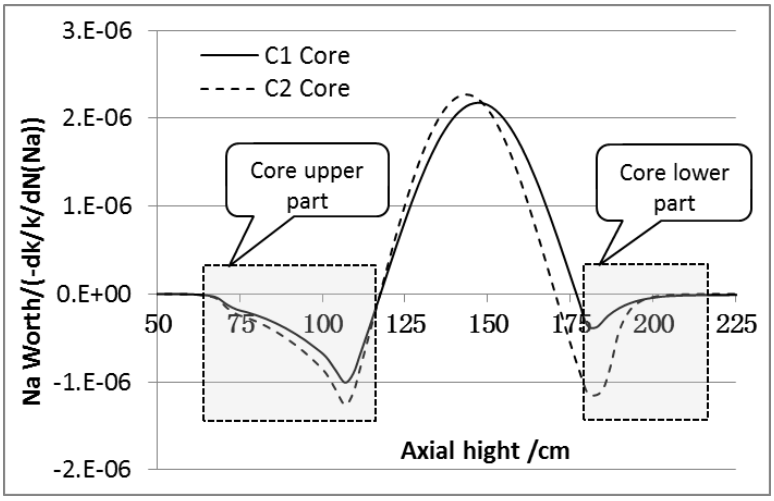

FIG. XXVI-13. Axial distribution of sodium reactivity worth in C1 and C2 cores (in maximum powered fuel sub-assembly).

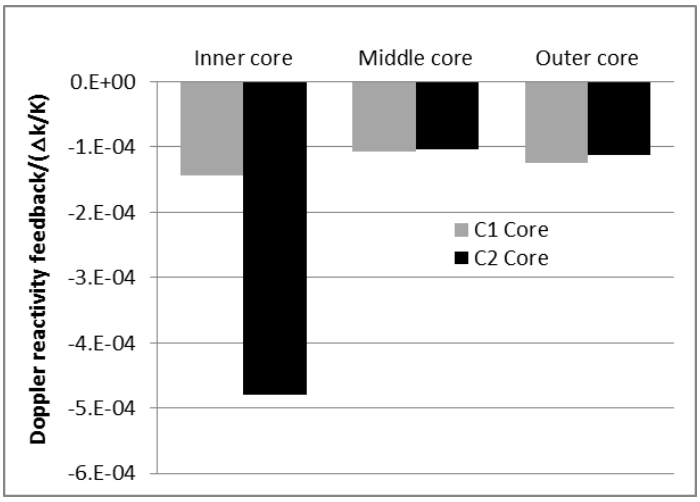

FIG. XXVI-14. Doppler feedback distribution by fuel zones in C1 and C2 cores.

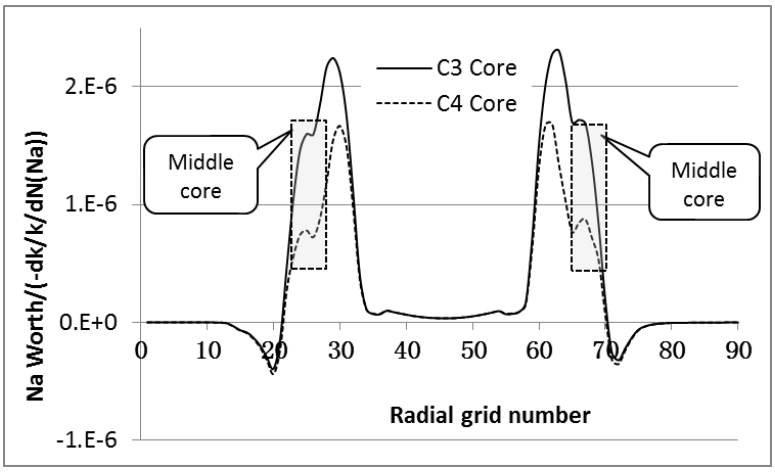

FIG. XXVI-15. Radial distribution of sodium reactivity worth in C3 and C4 cores (in central row on a central plane, the abscissa is grid number in calculation).

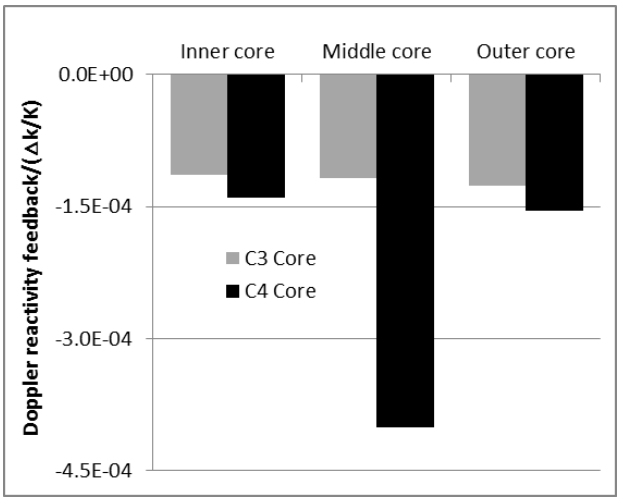

FIG. XXVI-16. Doppler feedback distribution by fuel zones in C3 and C4 cores.

XXVI-3.4. MA transmutation effect

MA transmutation effect (MA net consumption, including convertion to other actinides by capture reaction) is described in Table XXVI-9 with a standard core with 5 weight% MA addition as reference. In MA burner, due to increased neutron leakage, MA transmutation ratio is reduced, but net MA disappearance is larger since MA loading is increased.

TABLE XXVI-9. MA TRANSMUTATION EFFECT IN MA BURNER

	Reference core with 5 weight % MA	C1	C2	C3	C4
MA loading mass, kg	632.3	1340.7	942.5	1600.1	1096.0
MA transmutation ratio, %	8.333	7.605	6.032	6.835	6.517
Specific support ratio by MA transmutation, kg/GW(th)year	57.9	207.7	129.7	191.9	125.3

It is known that in order to reduce the long-term radiotoxicity, MA disappearance by fission reaction, also referred to as MA incineration, is more important than that by capture reaction. Two parameters, specific consumption by incineration and incineration ratio, are being used to compare MA incineration effect in burner with reference core. The MA specific consumption by incineration means the mass of MA fissioned normalized to per unit power output, and MA incineration ratio means the mass ratio of MA fissioned to MA loading. Table XXVI-10 presents fuel burn-up and MA incineration effect in C1-C4 cores, while also setting standard core (mentioned in Section 1.2 of this Annex) with 5 weight% MA addition to HM fuel as the reference core.

The calculation results show that fuel burn-up is similar to reference core, which amounts to around 70.8-80.2 GWday/tHM, but the Pu fraction in HM is increased in burner with increase of neutron leakage, thus MA incineration ratio in the burner is reduced when compared to the reference core. On the other hand, since the fraction of MA fission in the burner is higher than that in the reference core, the specific consumption of MA by incineration is larger than that in the reference core, which results in the supporting ratio of MA incineration reaching 7.0 and 6.7, respectively, in C2 and C4 cores, while it is only 3.1 in

the reference core. Meanwhile, sodium void reactivity in C2 and C4 cores is smaller than that in the reference core, as shown in Table XXVI-8.

It should be noted that further increase of MA fission fraction in critical fast reactor is very difficult. In the two strata fuel cycle concept, or more specifically, the strategy of LHLW transmutation cycle separation from commercial power generation cycle, ADS systems might be able to achieve higher whole-core MA fission fraction.

TABLE XXVI-10. MA INCINERATION EFFECT IN BURNER CORE

	Reference core	C1	C2	C3	C4
MA loading mass, kg	632.3	1340.7	942.5	1600.1	1096.0
Avg. fuel burn-up, GWday/t	73.9	80.2	70.8	78.0	73.0
MA incineration ratio, %	2.93%	2.67%	2.16%	2.43%	2.19%
MA fission fraction, %	5.5%	19.6%	12.5%	18.3%	11.9%
MA specific consumption by incineration, kg/GW(th)year	20.4	73.0	46.4	68.4	44.1
Supporting ratio of MA incineration	3.1	11.1	7.0	10.4	6.7

XXVI-4. CONCLUSIONS

The Annex presents the studies of the neutronic characteristics of two approaches to transmutation of MA nuclides in sodium cooled fast reactors, including TRU multi-recycling and transmutation in dedicated burner reactors. The main conclusions are as follows:

1) TRU multi-recycling mode

Loading TRU as driver fuel will have little impact on core kinetic parameters (β_{eff} , burn-up reactivity swing and Doppler feedback), core neutron flux distribution, or power density distribution, but the sodium void worth will be increased to a small positive value and the core breeding ratio will be slightly reduced.

In comparison with the reference core, the most significant advantage of TRU fuelled core is that in-core MA is consumed favourably with fuel burn-up, which means the MA are transmuted. The consumption rate of TRU in TRU fuelled core is ~18.8% larger than that in the reference core for the first TRU cycle.

When TRU is multi-recycled, for metal fuel the composition of TRU will achieve an equilibrium state, and the final MA equilibrium fraction in TRU will equal ~3.8%; for MOX fuel (reference core) the situation will be slightly different, as the MA fraction first decreases to minimum 7.2% and then increases slowly with accumulation of Cm. Meanwhile, the associated TRU heat release and neutron emission rate are much lower in discharged metal fuel than in MOX fuel, especially when TRU is recycled for a certain number of periods. The equilibrium fraction of fissile ^{239}Pu and ^{241}Pu in Pu for MOX fuel and metal fuel is 54% and 64%, respectively.

It can be concluded that this kind of a closed fuel cycle strategy, i.e., loading integrated TRU from PWR spent fuel as driver fuel and multi-recycling it in the reference core, has significant advantages and is feasible from the neutronics point of view. First, the proliferation resistance will be enhanced while the high utilization of uranium resources in fast breeders is maintained; second, the overall cumulative inventory of MA in nuclear power industry can be controlled effectively, and all of the MA would be stored in reactor cores

without any need for out-of-core storage. Grouped TRU recycling in fast reactors can make contributions to both breeding and transmutation, and is thus a prospective closed fuel cycle strategy to achieve the goal of sustainable development of nuclear energy.

2) Dedicated MA burner mode

The design study was carried out for a dedicated MA burner reactor core, and two sodium cooled fast burner cores with power levels of 1000 and 1240 MW(th) respectively (C2 and C4 cores) were considered. The whole-core MA fission fraction reaches the value of ~12% with the sodium void reactivity only ~4$; a relatively high supporting ratio of MA incineration of about 7.0 is achieved with MA incineration ratio of about 6.5% for one cycle in the burner core. These results indicate that complete incineration (fission) of all of the MA generated can be achieved using only 12% of MA burner's capacity. It also should be noted that in the MA burner reactor core β_{eff} is about 320 pcm, which is about 85% of that in a conventional fast reactor using Pu as fuel, and the Doppler constant is approximately -240 pcm, which is much lower than that in a conventional fast reactor.

In addition, the study shows that while increasing neutron leakage can effectively reduce reactor core sodium void reactivity, the MA incineration ratio will also be slightly decreased. For MA burner reactor in the two strata cycle strategy, when pursuing a greater supporting ratio of MA incineration (for example, more than 7.0 in the present study), higher MA fission fraction is required, therefore ADS system might possibly be a more technically suitable option.

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