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Neutronic Study on Ac-225 Production for Cancer Therapy by (n,2n) Reaction of Ra-226 or Th-230 Using Fast Reactor Joyo

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Abstract: Ac-225 has lately drawn considerable attention as a radioisotope for targeted alpha therapy treatment for certain types of prostate, blood-derived, and disseminated cancers, but its supply is limited. Therefore, we investigated the production method of Ac-225 by nuclear transmutation in a fast neutron reactor. The authors investigated irradiation of Ra-226 or Th-230 as a target nuclide in the experimental fast reactor Joyo, owned and operated by Japan Atomic Energy Agency, which has abundant fast neutrons and a large loading region with high heat removal capacity. Ra-226 is in increasing demand as a target nuclide to produce Ac-225. Therefore, as another option, we selected Th-230, which is 50 times more abundant than Ra-226 in natural uranium, as an alternative nuclide. Irradiation of Ra-226 and Th-230 with high energy neutrons above the threshold causes an (n,2n) reaction, producing Ra-225 and Th-229, respectively, which are the parent nuclides of Ac-225. The analyses showed that 47 GBq of Ac-225 can be generated annually by irradiating 1 g of Ra-226, and 6.5 GBq of Ac-225 can be semi-permanently generated every year by one-time irradiation of 50 g of Th-230 for 10 years (5 EFPY). It can be concluded that 100 MWt Joyo has potential to produce more than 70% of the current global supply of Ac-225 and/or to generate the parent nuclide Th-229, which keeps producing Ac-225 for thousands of years.

Keywords: targeted alpha therapy; Ac-225; fast reactor; fast neutrons; Joyo; Ra-226; Th-230; (n,2n)

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1. Introduction

Targeted alpha therapy (TAT) studies [1,2] have been conducted for the treatment of prostate, blood-derived cancers, disseminated cancers, etc. Among alpha-decay radionuclides, treatment of bone prostate cancer with Ac-225 is 14 times more effective than Ra-223. The development of alpha-emitting radiopharmaceuticals for TAT is an active area of academic and commercial research around the world. However, the supply of alpha-emitter does not meet growing demand. Currently, Ac-225 is mainly generated from ORNL's, ITU's, and IPPE's Th-229, which is a parent nuclide of Ac-225, and the annual production amount is limited to about 63 GBq [3]. Methods for generating it, especially using some types of accelerators with different transmutation paths, are proposed and developed in several countries.

As an Ac-225 production method, a spallation method in which Th-232 is irradiated with high energy protons, is being studied. According to TRIUMF, it is reported that irradiation with 500 MeV of protons has the potential to generate 11.3 TBq of Ac-225 every month [3]. Producing many kinds of impurities owing to broadening the yield shape of spallation products is a challenge in the post irradiation process. It has also been reported that when Ra-226 is irradiated with 20 MeV protons using a low-energy cyclotron, it has the potential to produce 4 TBq of Ac-225 every month through the (p, 2n) reaction [3]. In addition, a method of irradiating Ra-226 with an electron beam using an electron linear accelerator and producing an Ra-225/Ac-225 generator by a (γ, n) reaction is also being

studied. It is reported that this method has the potential to generate 48 GBq per month from 1 g Ra-226 source [3]. The IAEA-JRC WORKSHOP announced in 2018 that the US Department of Energy has an annual supply capacity of approximately 37 GBq of Ac-225 by milking from Th-229 [4]. JSC "SSC RF–IPPE" also extracts Ac-225 by milking from Th-229 and has an annual supply capacity of about 15 GBq [5].

Niowave presented the possibility of production more than 18 TBq of high purity Ac-225 annually by the (γ, n) reaction of Ra-226 using a superconducting electron linear accelerator [6]. Argonne's Low Energy Accelerator Facility (LEAF) also shows the capability of producing 37–74 GBq of Ac-225 weekly by the (γ, n) reaction of Ra-226 using an electronic linac [7]. The method of irradiating Th-232 with a proton beam, developed at the Institute of Nuclear Research of Russian Academy of Sciences (INR), similar to TRIUMF has the ability to generate approximately 74 GBq of Ac-225 in 10 days by the (p, x) reaction [8]. The Argentine α project indicates potential to produce about 1.1 TBq of Ac-225 annually by the (p, 2n) reaction of Ra-226 using a cyclotron [9].

As summarized above, research and development of Ac-225 production methods using accelerators are being actively carried out worldwide. Those methods have the advantage of being able to generate Ac-225 from a small amount of target nuclides with high efficiency. On the other hand, the method using a nuclear fission reactor also has different advantages such as high neutron fluence due to the stable and high neutron flux over a long period of time, large volume of irradiated area, large heat removal capacity, and excellent energy balance without requiring external energy supply.

In this study, the neutronic analysis by Monte-Carlo simulation was performed to study the potential of mass production of high purity Ac-225 using existing fast reactor "Joyo" in Japan. Two species of target nuclides for fast neutron irradiation were considered. One is Ra-226, which is commonly used to produce Ac-225, and the other one is Th-230, which is a more abundant, naturally occurring nuclide as an alternative. The demand for Ac-225 is predicted to grow more and more in the future, so that having various production routes is considered to be desirable and essential.

2. Ac-225 Generation Process

There are multiple pathways for neutron-induced transmutation to generate Ac-225. Since Ac-225 is in the neptunium series, Ac-225 can be produced if the parent nuclides included in this series can be prepared. Figure 1 shows the decay chain from Np-237 to Ac-225.

The spent fuels discharged from conventional light water reactors contain roughly 0.6 kg/ton-HM of Np-237, which produces Ac-225 as daughter nuclides. However, Np-237 is known as the longest half-life nuclide ($T_{1/2}$ = 2.1 $\times$ 10^6 years) in the high-level waste, and the succeeding daughters—U-233 ($T_{1/2}$ = 1.6 $\times$ 10^5 years) and Th-229 ($T_{1/2}$ = 7.9 $\times$ 10^3 years) in the decay chain—also have long half-lives, so that the production rate of Ac-225 is very small. Similarly, a method is conceivable in which U-233 is produced by replacing a part of the uranium fuel used in the current commercial nuclear reactors with Th-232 fuel. This method is available only in the future when thorium fuel cycle is introduced into commercial nuclear power generation on a large scale.

The next method the authors considered is to produce a parent nuclide with a shorter half-life, which decays to Ac-225, by neutron irradiation in existing fission reactors. The parent nuclide of Ac-225 with atomic mass number A in the neptunium series can be produced by the (n,2n) reaction of a nuclide having mass of A + 1. Therefore, as irradiation targets, we focused on the nuclides Ra-226 and Th-230, which are noble but slightly present in nature as daughter nuclides in the uranium series. When Ra-226 is irradiated with fast neutrons, it undergoes transmutation to Ra-225 by the (n,2n) reaction in the high-energy region. The threshold value is 6.4 MeV. The β-decay nuclide Ra-225 ($T_{1/2}$ = 14.9 days) promptly decays to Ac-225. Similarly, when Th-230 is irradiated with fast neutrons, it undergoes transmutation to Th-229 ($T_{1/2}$ = 7.9 $\times$ 10^3 years) by the (n,2n) reaction the threshold energy of 6.8 MeV. Th-229 steadily decays to Ra-225 by emitting alpha particles

and reaches to Ac-225. In terms of their abundances, 3 tons of natural uranium in radioactive equilibrium contains about 1 g of Ra-226 and about 50 g of Th-230. The abundance values for each nuclide obtained by decay series calculation using ORIGEN2.2 code [10] are listed in Table 1.

Table 1. Composition of nuclides in radioactive equilibrium in 3 tons of natural uranium.

Uranium Series	
Nuclide	**Amount (g)**
U-238	2.98×10^{6}
U-234	1.61×10^{2}
Pa-234	6.51×10^{-10}
Pa-234m	1.44×10^{-9}
Th-234	4.32×10^{-5}
Th-230	$\boldsymbol{4.86 \times 10}$
Ra-226	***1.01***
Rn-222	6.51×10^{-6}
Po-218	3.60×10^{-9}
Po-214	3.12×10^{-15}
Po-210	2.23×10^{-4}
Bi-214	2.27×10^{-8}
Bi-210	8.07×10^{-6}
Pb-214	3.05×10^{-8}
Pb-210	1.31×10^{-2}
Pb-206	2.60×10^{6}

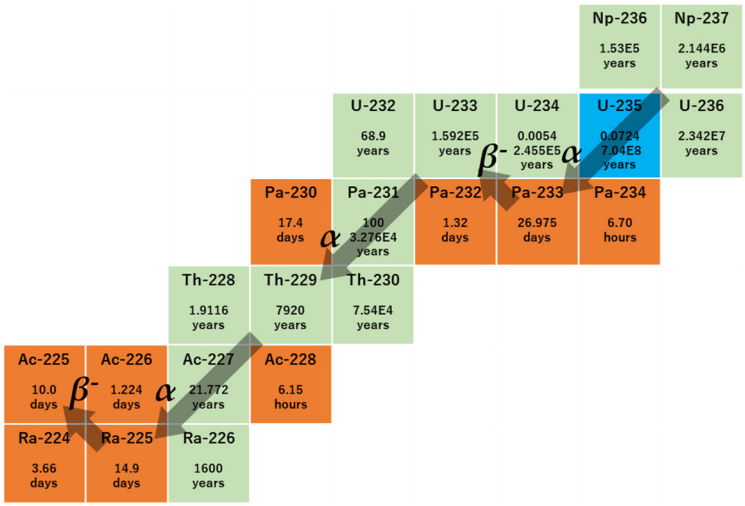

Figure 1. Decay chain of neptunium series (from Np-237 to Ac-225) [11].

During irradiation of Ra-226 under fast neutron spectrum, the undesirable parent nuclide Ra-227 of Ac-227, which emits β^- rays with a relatively long half-life of 21.8 years, is generated simultaneously. In order to use the produced actinium element directly (namely, without isotope separation) for TAT, it is necessary to ensure the required purity for Ac-225. A conceptual schematic flow of twice chemical separations between radium and actinium to obtain high-purity Ac-225 is drawn in Figure 2.

In the case of Ra-226 irradiation, the major elements produced are radium, actinium, and thorium. The ratio of radioactivity for those elements are about 99%, about 1%, and about 0.01% or less, respectively. In the first step of this process, the radium target discharged from the center of the core is cooled for 8 days. Almost all Ra-227 ($T_{1/2}$ = 42.2 min) decays out rapidly, but Ra-225 ($T_{1/2}$ = 14.9 days) disintegrates only about 30% during 8 days of cooling. After this cooling period, the primary chemical separation [12] is performed

using DGA resin to separate radium and actinium. Actinium is adsorbed onto DGA resin in a nitric acid solution. The adsorbed actinium, which contains Ac-227, is discarded. Since the main isotopes remaining at this point are Ra-225 and Ra-226, further cooling produces Ac-225 through β^- decay of Ra-225 with 14.9 days of half-life. By performing the secondary separation, high purity Ac-225 can be recovered by adsorbing the Ac-225 onto DGA resin. The remaining Ra-226 is recycled as the new irradiation target.

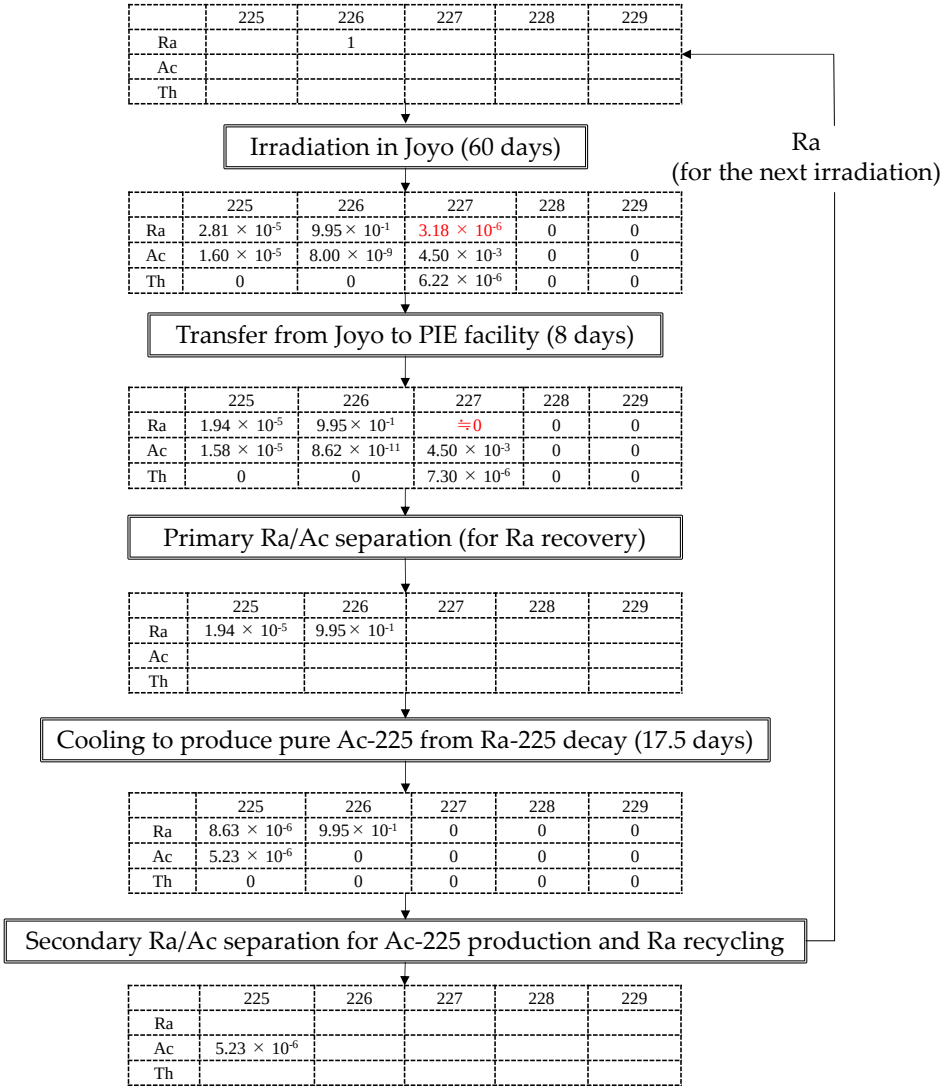

Figure 2. Ac-225 separation/generation scheme in the case of 1 g of Ra-226 irradiation (values in tables are isotope mass in gram unit).

The schematic flow of the post irradiation for the Th-230 case is shown in Figure 3. The main nuclides in the discharged Th-230 target are radium, actinium, thorium, protactinium, and uranium. After 10 days of cooling, the thorium is recovered by chemical separation using DGA resin. It is adsorbed onto DGA resin in a nitric acid solution, which has a lower concentration than that used to separate actinium. The main isotopes of recovered thorium are Th-228, Th-229, and Th-230. Among them, Th-229 is the parent nuclide of Ac-225. Th-231 ($T_{1/2}$ = 1.063 days), which produces the impurity Ac-227 by α-decay, has disappeared immediately due to rapid radioactive decay. Through further cooling of the thorium for about 30 days (without Th-231), Th-229 undergoes single α-decay Ra-225 and reaches radioactive equilibrium. From there, Ac-225 is produced by β-decay. Therefore, high purity Ac-225 can be obtained by milking from Th-229 cow nuclide. Since Th-229

has a long half-life of 7920 years, semi-permanent milking to produce Ac-225 is possible without repeated irradiation of Th-230.

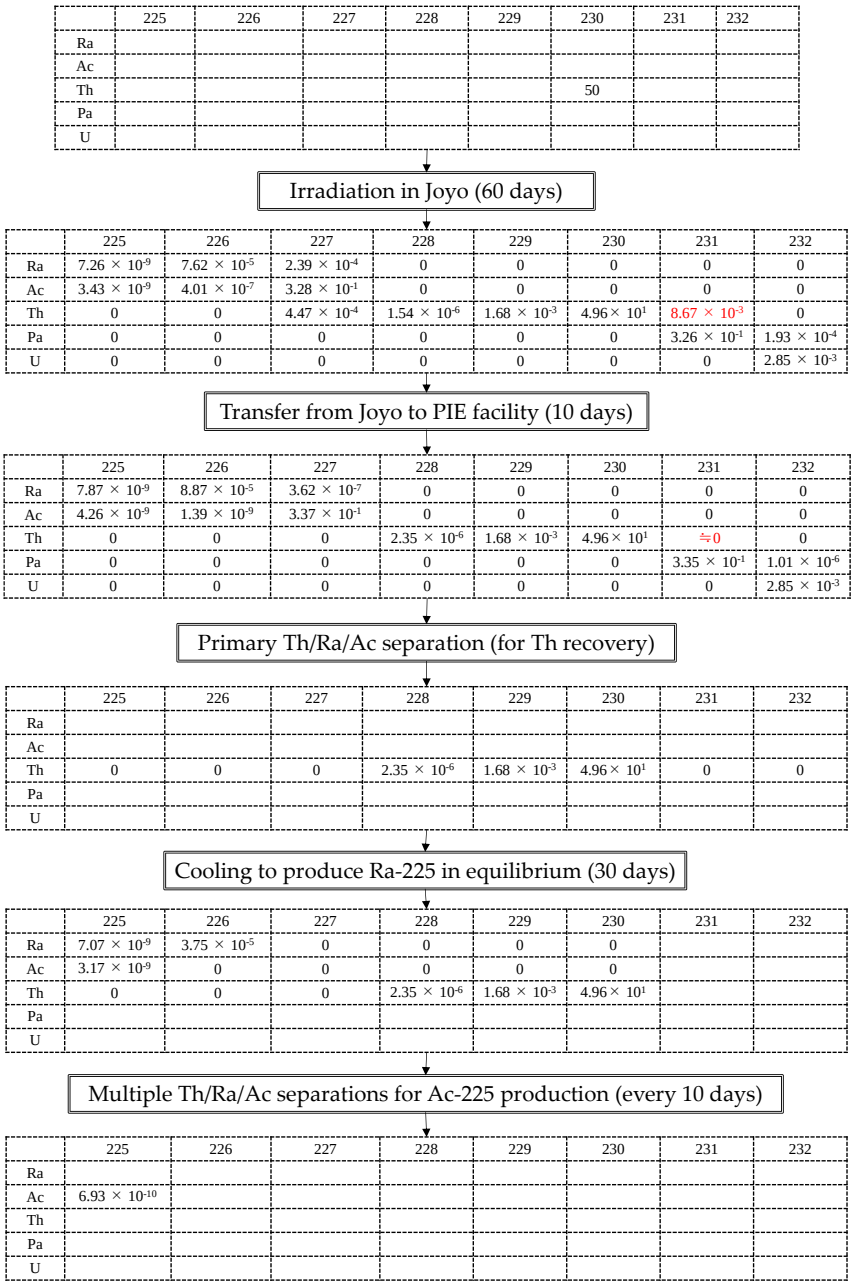

Figure 3. Ac-225 separation/generation scheme in the case of 50 g of Th-230 irradiation (values in tables are isotope mass in gram unit).

3. Analysis Conditions

3.1. Core Configuration of the Experimental Fast Reactor Joyo

The neutronic potential of the experimental fast reactor Joyo for Ac-225 production was evaluated for the most recent core named MK-IV with 100 MWt thermal rating. Joyo has been owned and operated by JAEA (Japan Atomic Energy Agency, Tokai-mura, Japan) since 1977 and currently is the only fast neutron irradiation facility available within the OECD (Organisation for Economic Co-operation and Development, Paris, France) member countries. The core fuel arrangement, main specifications, and neutron spectra of Joyo are shown in Tables 2 and 3, and Figure 4.

Table 2. Main specifications of the Joyo.

Reactor power (MWt)	100
Core height (cm)	50
Core equivalent diameter (cm)	78
Number of fuel subassemblies	79
Installable number of irradiation rigs	4
Fissile material mass (kg)	250
Coolant temperature (°C) (Inlet/Outlet)	350/456
Cycle length (days)	60
Annual operation frequency (/year)	3

Table 3. Fuel specifications.

Theoretical density (%)	94
Pu content (wt%)	29 (outer fuel)/22 (inner fuel)
Isotopic composition of Pu (wt%) Pu238/Pu239/Pu240/Pu241/Pu242/Am241	1/66/24/4/3/2
U235 enrichment (wt%)	18 (outer fuel and inner fuel)

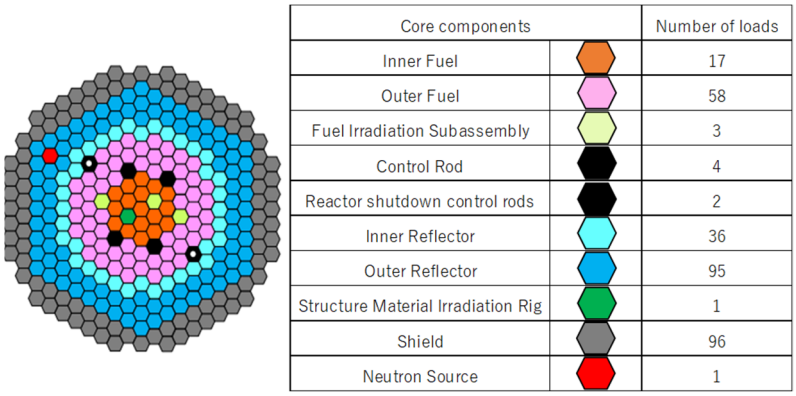

Figure 4. Core configuration of Joyo MK-IV.

One prominent feature of the core characteristics of Joyo is high neutron flux with hard spectrum. This feature is suited for causing (n,2n) reactions when Ra-226 or Th-230 is used as an irradiation target. Figure 5 shows neutron spectrum at some locations in Joyo MK-III core [13]. In the current MK-IV core, the total thermal power has been slightly reduced from 140 MW to 100 MW compared to MK-III to satisfy the revised regulations after the accident of the TEPCO's Fukushima Daiichi NPS in 2011. Hence, the maximum neutron flux is reduced by about 30%.

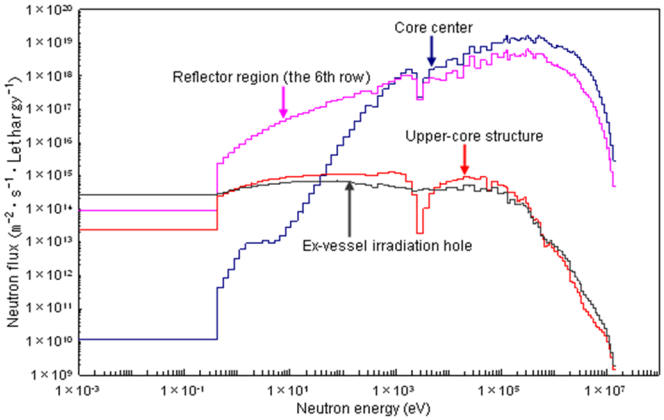

Figure 5. Neutron spectrum in Joyo (MK-III core).

There are four types of fuel irradiation assemblies and three types of material irradiation assemblies in Joyo. In order to increase the degree of flexibility in the geometric shape and volume of the irradiation target, the utilization of a structure material irradiation rig with a larger irradiation volume (>1000 cm^3) was assumed in the neutronic calculations. Figure 6 shows the shape of the structure material irradiation rig [12]. It is assumed that the irradiation target is loaded in the central position out of the seven sample loading capsules. The chemical form of the irradiation target is assumed to be radium metal or thorium oxide, the density is 5.5 g/cm^3 and 10 g/cm^3, respectively. The load amount was 1 g for Ra-226 or 50 g for Th-230 (57.4 g for ThO_2). These are the amounts contained in about three tons of natural uranium. When irradiating radium, it is necessary to load the capsule in a sealed state. Nevertheless, Th-230 is a fertile nuclide, the thorium oxide target must be covered with a cladding tube because it is categorized as nuclear material.

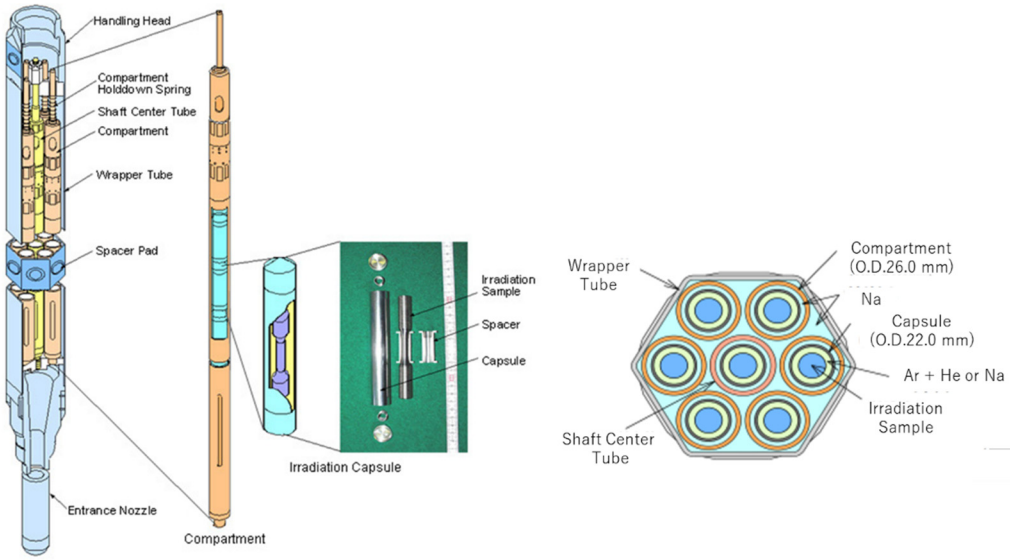

Figure 6. Structure material irradiation rig.

The standard operation cycle of the Joyo core is about 120 days, which is the sum of the operation period with rated output of about 60 days and the suspension period for periodic inspection and fuel reloading of about 60 days. The irradiated targets can be discharged in a minimum of 6 days after the end of operation.

3.2. Analytical Model and Calculation Conditions

Burnup calculation was performed by using a continuous-energy Monte-Carlo burnup code MVP-BURN developed by JAEA [14], and decay calculation was implemented using ORIGEN 2.2 to evaluate the production rate of Ac-225. The MVP-BURN code consists of the MVP, which is a transport calculation code based on the continuous-energy Monte-Carlo method, and the BURN module, which calculates the nuclide composition based on the reaction rate for each burnup region. The authors added several missing nuclides in the burnup chains prepared in the MVP code, such as Ra-225, Ra-226, Ra-227, Ac-225, Ac-226, Th-227, Th-228, Th-229, Th-230, Th-231, Pa-231, Pa-232, U-232, and U-233.

In order to perform accurate evaluation of the nuclear reaction rates in Joyo core, huge input data necessary for the three-dimensional system simulation was prepared. Those data include geometric and compositional information of inner fuel assemblies, outer fuel assemblies, fuel irradiation subassemblies, reflectors, etc. shown in Figure 4 and summarized in Tables 2 and 3.

In order to maximize the transmutation efficiency, the irradiation target is assumed to be loaded in the center of the capsule within the structure material irradiation rig, and the surrounding sample holders are assumed to be filled with helium gas to prevent parasitic

absorption and moderation of neutrons, which causes flux loss and spectrum softening. Actual irradiation requires target sealing; thus, a simple calculation was performed to evaluate the effect of the thickness of SUS cladding tube covering the irradiation target on reaction rates. Since the results showed that the presence of cladding tube with 1mm thickness or absence of it has a negligible difference on transmutation efficiency, the irradiation calculations were performed with the target nuclide bare. Figures 7 and 8 show a cross-sectional view of the whole core and an enlarged view of an irradiation rig loaded with Ra-226 or Th-230, drawn by visualization function of MVP. Table 4 shows the specifications of the irradiation target.

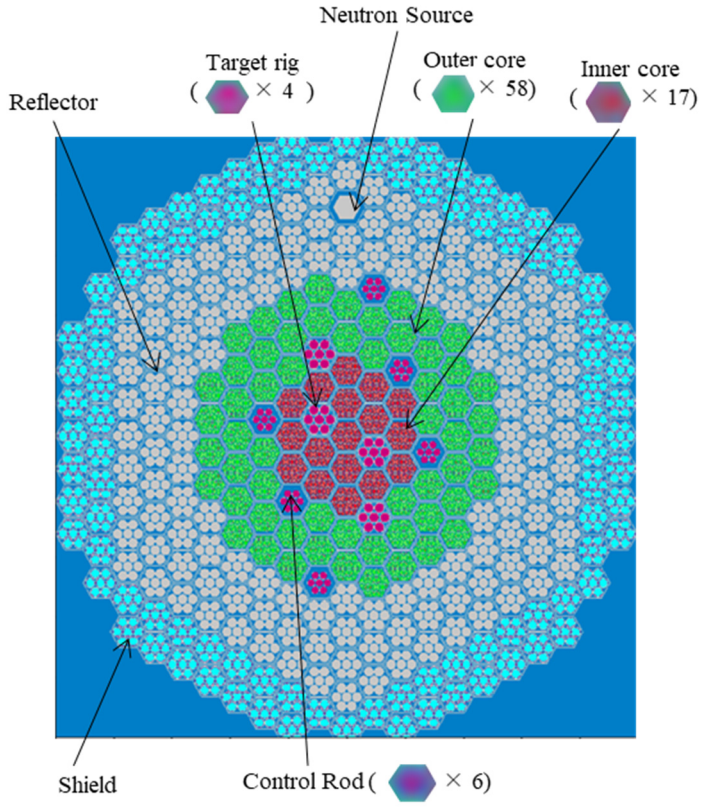

Figure 7. Cross-sectional view of the Joyo core prepared for 3D Monte-Carlo calculation (drawn by visualization function of MVP).

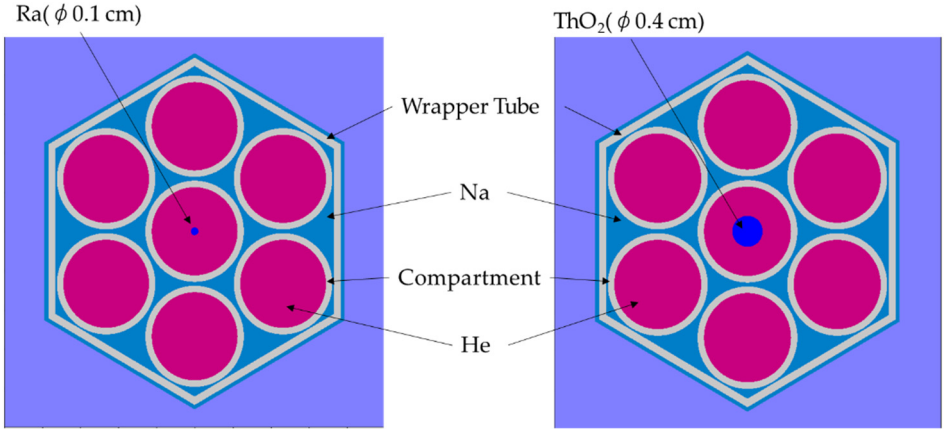

Figure 8. Cross-sectional view of the irradiation rig loading with the target material for 3D Monte-Carlo calculation (drawn by MVP input data) (Left: Ra-226, Right: Th-230).

Table 4. Irradiation target specifications.

	Ra	ThO_2
Diameter (cm)	0.1	0.4
Height (cm)	5.8	11.4
Volume (cm^3)	0.18	5.74
Density (g/cm^3)	5.5	10
Mass of target (compound) (g)	1	57.4
Mass of target isotope (g)	1 (Ra-226)	50 (Th-230)

Burnup calculations using MVP-BURN were performed under the Joyo's operating conditions of 100 MWt of thermal output, 60 days per cycle, and a cooling period of 8 or 10 days. This cooling period was determined by considering the time required for sufficient decay of the Ra-227 and Th-231, the parent nuclides of Ac-227, and for removal of the irradiation target after shutdown. The number densities of isotopes obtained by MVP-BURN were used as initial values for the following decay calculation by ORIGEN2 to evaluate the amount of Ac-225. Since Ra-227 ($T_{1/2}$ = 42.2 min) is not included in the data library of ORIGEN2, instant decay of Ra-227 to Ac-227 was assumed.

4. Analysis Results

4.1. Irradiation Analysis of Ra-226

Figure 9 shows the composition of the major nuclides during and after neutron irradiation of Ra-226 for 60 days in the irradiation rig at the center of the Joyo core.

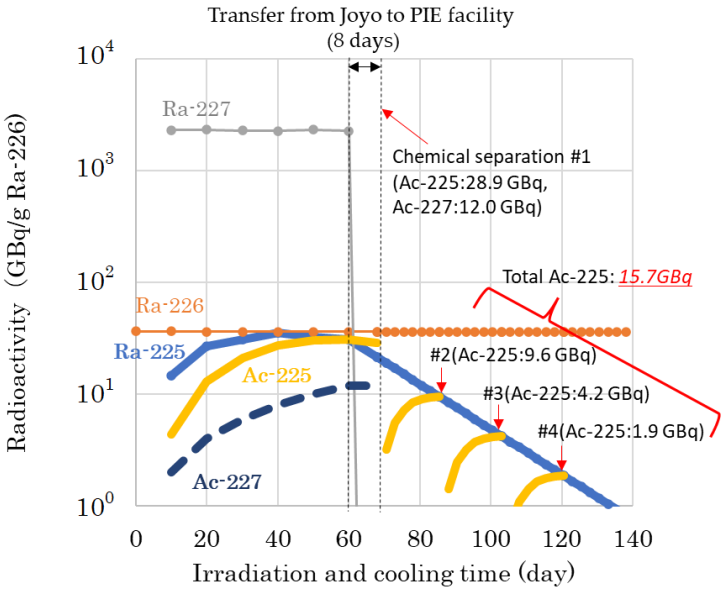

Figure 9. Isotopic composition changes of Ra-226 (1 g) by neutron irradiation for 60 days in Joyo and pure Ac-225 production through succeeding Ra/Ac chemical separations.

In case of Ra-226, about 30 GBq of Ac-225 is produced after 60 days of irradiation and 8 days of cooling. However, this actinium contaminates about 10 GBq of impure Ac-227. Meanwhile, Ra-227 ($T_{1/2}$ = 42.2 min), the parent nuclide of Ac-227, completely decays out after 8 days of cooling. As described in Figure 2, only radium is recovered from the irradiated target after discharge and all actinium is discarded because of the presence of Ac-227 in the primary chemical separation process. By cooling the extracted radium, Ra-225 produces Ac-225 through β-decay, and the radioactivity of Ac-225 reaches its maximum after 17.5 days. Then, a secondary chemical separation between radium and actinium produces high purity Ac-225. One cycle (60 days) of irradiation of Ra-226 in Joyo with three times milking every 17.5 days produces about 15.7 GBq of pure Ac-225. Since this

operation can be repeated three times per year, triple the amount of Ac-225 can possibly be produced by Joyo.

4.2. Irradiation Analysis of Th-230

Figure 10 shows the composition of the major nuclides during and after 60 days of neutron irradiation of Th-230 in the irradiation rig loaded at the center of the core.

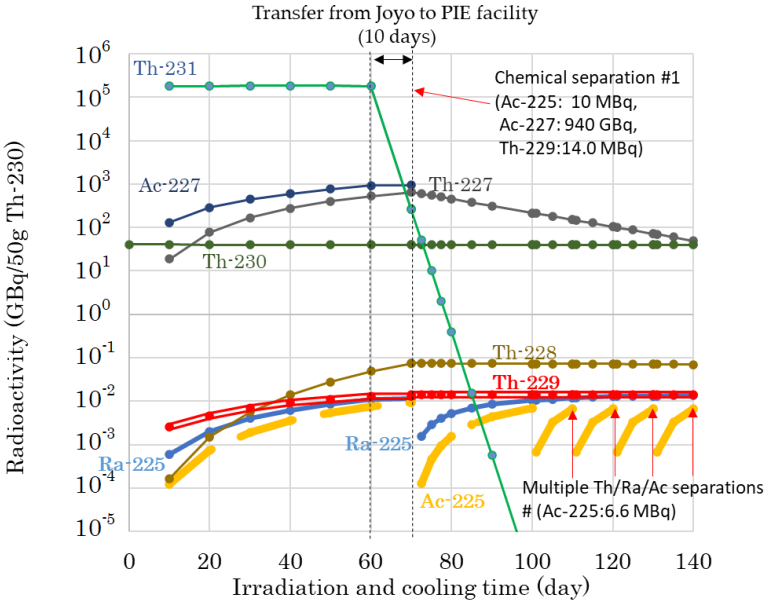

Figure 10. Isotopic composition changes of Th-230 (50 g) by neutron irradiation for 60 days in Joyo and pure Ac-225 production through succeeding Th/Ra/Ac chemical separations.

In the case of loading Th-230, about 10 MBq of Ac-225 and 14 MBq of Th-229 are produced after 60 days of irradiation and 10 days of cooling. However, as shown in Figure 10, the radioactivity of Ac-227 is about 100,000 times larger than that of Ac-225 just after the irradiation. Therefore, only thorium is recovered by chemical separation, and all other nuclides including actinium are discarded. Moreover, the thorium in the target just after the irradiation contains Th-231 ($T_{1/2}$ = 1.063 days), which is the parent nuclide of Ac-227. Hence, it is necessary to have a 10-day cooling period at least for the recovered thorium before implementing secondary separation to recover pure Ac-225.

Through further cooling of the thorium (without Th-231), Th-229 undergoes single α-decay with β-decay to produce Ac-225. However, the impurity nuclide Ac-227 is produced from the slightly remaining Th-231; it is about one hundred thousandth of Ac-225 radioactivity. After further cooling for about 30 days, Ra-225 reaches radioactive equilibrium. After that, Ac-225 is semi-permanently obtained by milking from Th-229. For the Ra-226 irradiation case, milking was performed after cooling for 17.5 days, but in this case, a different milking interval is preferable as explained below because Ra-225, which is the parent nuclide of Ac-225, does not decrease due to the incessant supply from Th-229.

Figure 11 shows the correlation between the interval of Th-229/Ac-225 milking and Ac-225 annual production amount. The longer the milking interval, the larger the amount of Ac-225 is produced at one time, but the annual Ac-225 production decreases. Meanwhile, a single dose of about 6 MBq [15] is required to achieve a therapeutic effect in prostate cancer. Accordingly, the time interval is determined as 10 days in which 6 MBq of Ac-225 is accumulated. This time interval corresponds to annual Ac-225 production of about 240 MBq. Although this amount is smaller compared to that of the Ra-226 case, the production amount of Th-229 can be increased almost proportionally with irradiation time owing to the very long half-life of Th-229, which never saturates by radiative decay.

Hence, by extending the irradiation period to 30 cycles (5 EFPY), 6.5 GBq of Ac-225 can be produced annually by a single irradiation of Th-230.

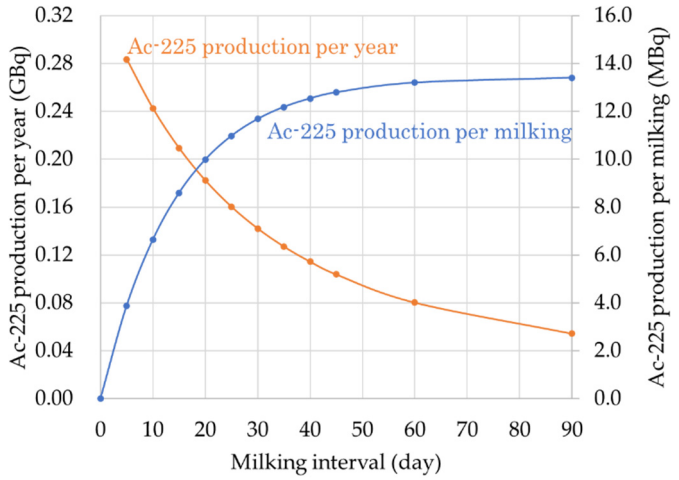

Figure 11. Correlation between time interval of Th-229/Ac-225 milking and annual Ac-225 production (from 14 MBq of Th-229 produced through 60 days irradiation of 50 g of Th-230).

4.3. Material Composition Effect on Neutron Spectrum and Reaction Rate

The target nuclide Ra-226 is a rare nuclide that exists only about 1 g in 3 tons of natural uranium. On the other hand, the other target, Th-230, is about 50 times more abundant than Ra-226. Therefore, it is desirable to minimize the loss of conversion to unnecessary nuclides, especially for Ra-226. It is effective to harden the neutron irradiation spectrum to maximize the production of Ac-225 by (n,2n) reactions and simultaneously minimize the loss of the rare irradiation target by (n,γ) reactions. Accordingly, the correlation between fuel, cladding, and coolant compositions and cross sections of Ra-226 were evaluated. The examined combinations of core materials are listed in Table 5.

Table 5. Material combinations of fuel, coolant, and cladding for hardening the neutron spectrum.

CaseID	
Reference (original) combination	
(I) MOX/Na/SUS (fuel/coolant/cladding)	
Hypothetical combinations	Realistic combinations
(II) MOX/***Void***/SUS	(II′) MOX/***He***/SUS
(III) MOX/Na/***Void***	(III′) MOX/Na/***SiC***
(IV) ***U-Pu***/Na/SUS	(IV′) ***U-Pu-Zr***/Na/SUS
	(V) ***U-Pu-Zr***/Na/***SiC***

Figure 12 shows that the (n, γ) cross section (σ_γ) decreases with an increasing fraction of fast neutron flux φ > 0.1 MeV, and the (n,2n) cross section (σ_{2n}) increases with an increasing fraction of extremely high energy flux φ > 6.4 MeV for different material combinations. The σ_γ shown by the solid line in the left part of the figure is the smallest for the case IV′, where the MOX fuel was replaced by the metallic fuel. The σ_{2n} shown by the dashed line was the largest in the case III′, where non-metallic structural materials were used. These results suggest that the spectra are affected by elastic scattering of oxygen in the low-energy region and inelastic scattering of the structural material metal elements in the high-energy region. The case V "U-Pu-Zr/Na/SiC", which combines the U-Pu-Zr ternary alloy fuel having the minimum σ_γ and the SiC structural material with the maximum σ_{2n} shows a preferably large $\sigma_{2n}/\sigma_\gamma$ ratio among realistic material combinations. In consequence, the $\sigma_{2n}/\sigma_\gamma$ ratio of this case V is larger by 46%, and the Ac-225 production was increased by 34% compared to case I "MOX/Na/SUS". Therefore, it was found that

selecting proper composition of the cladding and fuel potentially decreases the loss of conversion to unnecessary nuclides and increases the Ac-225 production in the sodium cooled fast reactor.

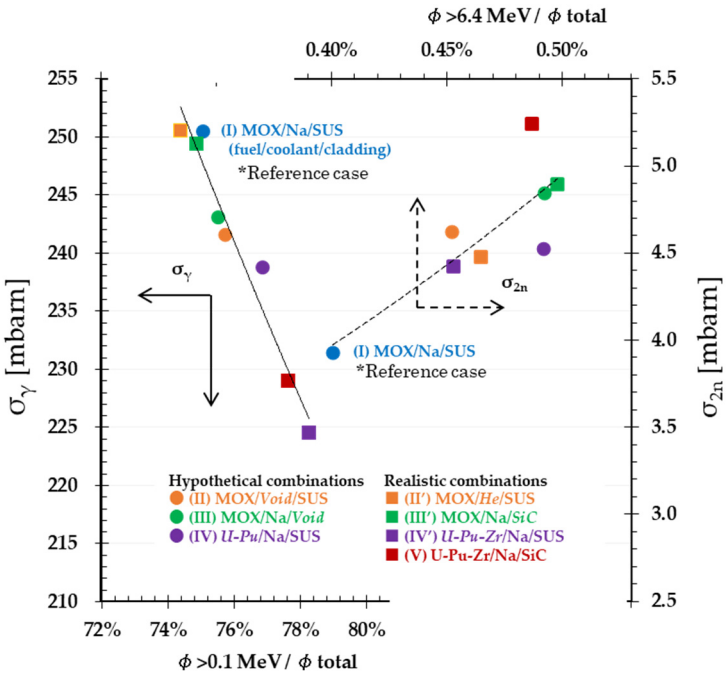

Figure 12. Correlation between fast neutron flux ratio for various core material combinations and $\sigma_{2n}/\sigma_{\gamma}$.

5. Conclusions

The authors investigated methods to generate Ac-225 from Ra-226 or Th-230 through (n,2n) reactions by irradiating fast neutrons using the existing experimental fast reactor Joyo. Ra-226 and Th-230 are contained in 3 tons of natural uranium at about 1 g and 50 g, respectively. In addition to precious Ra-226, which is well-known as a target nuclide to produce Ac-225, more abundant Th-230 were also examined as an alternative target nuclide. For both cases, Ac-225 is not directly produced, but indirectly produced through decay of Ra-225 or Th-229, which is generated by fast neutron-induced (n,2n) reaction from Ra-226 or Th-230, respectively.

It is assumed that 1 g of Ra-226 is loaded in the sample-loading capsule of the material irradiation rig located at the center of the core of Joyo. After one cycle (60 days) of irradiation and 8 days of cooling, about 30 GBq of Ac-225 and 10 GBq of Ac-227 are produced. After discharging the irradiation rig, all actinium produced in the capsule is discarded after Ra/Ac separation because it is contaminated with Ac-227. Milking the recovered radium (composed of Ra-225 and Ra-226) three times at 17.5 days intervals produces 15.7 GBq of pure Ac-225. Assuming reuse of Ra-226 after Ra/Ac separation and three times irradiation in one year, it is evaluated that about 47 GBq of Ac-225 can be produced annually from 1 g of Ra-226. This amount corresponds to about 70% of the current world supply.

In the case of irradiating Th-230, the production amount of Th-229 can be increased almost proportionally with irradiation time, owing to the very long half-life of Th-229, which never saturates by radiative decay. Hence, by extending the irradiation period up to 30 cycles (5 EFPY), 6.5 GBq of Ac-225 can be produced annually as daughter nuclides of Th-229 by a single irradiation of 50 g of Th-230 with succeeding Th-229/Ac-225 milking at intervals of 10 days. It should be emphasized that this Th-229 keeps producing Ac-225 for thousands of years with the constant rate.

In order to maximize Ac-225 production while minimizing the undesirable depletion of valuable Ra-226, some combinations of fuel, coolant, and cladding materials were

examined to achieve a higher $\sigma_{2n}/\sigma_{\gamma}$ ratio of Ra-226. When the oxide fuel was changed to metallic fuel (U/Pu/Zr) and the cladding material changed from SUS to SiC, it was confirmed that the production amount of Ac-225 could be increased by about 30% by neutron spectrum hardening.

These results indicate that Ra-226 irradiation under fast neutron spectrum is a suitable method for producing a large amount of Ac-225 in a short period of irradiation time, while the use of Th-230 target is preferable to produce the parent nuclide Th-229, which continuously generates Ac-225 for thousands of years by only one, long-term irradiation.

As a conclusion, fast spectrum reactors such as Joyo have a high potential for Ac-225 production. This method is advantageous to early implementation of Ac-225 production with low cost because it requires to use only an existing fast fission reactor and can be implemented on the side during the regular operation without any impact on the core performance and additional energy consumption.

The experimental fast reactor Joyo is currently idle to comply with new regulations that were tightened after the Fukushima Daiichi nuclear accident in 2011. The operation is scheduled to resume in a few years. The RI Production Subcommittee of the Japan Atomic Energy Commission formulated a new action plan in June 2022 to demonstrate the production of Ac-225 by FY2026. After the restart of Joyo, it will be performed by irradiating 10 mg-order of Ra-226 in the center of Joyo core.

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