Study on Transmutation of Fission Products at PNC

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ABSTRACT

Studies at PNC are described on transmutation of long-lived fission products by accelerator and by fission reactor. As for the accelerator, four transmutation methods are compared in terms of transmutation energy and transmutation rate. For the fission reactor, core design concept and core performance characteristic of transmutation reactor are presented.

High transmutation. rate and small transmutation energy are main requirements for the transmutation of fission products. Neither the accelerator nor the fission reactor could satisfy simultaneously both the requirements. Therefore, new transmutation methods which could satisfy both the requirements have been also studied at PNC. As the new transmutation methods, moving target method and inertial transmutation method are presented.

1. INTRODUCTION

Transmutation of long-lived radioactive nuclides into short-lived or stable ones has been studied to reduce the long-term radiotoxicity of high-level waste related to the permanent disposal in a stable geologic formation.

The long-lived nuclides in radioactive wastes are classified into fission products (FPs) and transuranic elements (TRUs). Since TRU has a potential of

fission, the transmutation of TRU has been studied by using TRU **as a** fuel in a fission reactor [1, 2]. In this paper, the transmutation of long-lived fission products is discussed.

High transmutation rate and small transmutation energy are main requirements for the transmutation of fission products. The transmutation rate of a radioactive **nuclide** in fission products should be several times or more faster than its natural decay rate. The transmutation energy required for one transmutation reaction of the target **nuclide** must not exceed the initial energy that is generated and is available in the fission process which produces this **nuclide.** In other words, the transmutation must meet the criterion of energy balance.

Accelerator and fission reactor may be applied to the transmutation of fission products. Since the accelerator is possible to create high flux by focusing particle beam, **the** transmutation by accelerator could satisfy the requirement of high transmutation rate. However, it is difficult to meet the energy balance criterion because the accelerator needs energy from outside to be operated. On the other hand, the transmutation by fission reactor could meet the energy balance criterion because the **fission** reactor generates energy and does not need the outside energy to be operated theoretically. The transmutation rate by fission reactor, however, is low compared with the one by accelerator, since high neutron flux is difficult to create due to no charge of neutron.

This paper shows the transmutation of fission products by accelerator and **fission** reactor. Four transmutation methods by accelerators are compared in terms of the transmutation energy and the transmutation rate. **Fission** reactor for transmutation is explained. The core design concept and the core performance characteristic of the reactor are presented. Recently,

we started to study new transmutation methods which could achieve both high transmutation rate and small transmutation energy simultaneously. We will introduce them also in this paper.

2. TRANSMUTATION BY ACCELERATOR

Various methods of transmutation of fission products have been proposed as follows:

(a) transmutation through **photonuclear** reaction by using **bremsstrahlung** from accelerated electron (electron method) [3, 4],

(b) transmutation through **spallation** reaction by high energy proton (proton method) [5, 6],

(c) transmutation through, **spallation-induced** neutron reaction, mostly (n, y) reaction, by use of secondary neutrons from high energy **proton**-induced **spallation** reaction (**spallation** neutron method) [3, 5] and

(d) transmutation through (n, 2n) reaction by use of high energy neutron generated by muon catalyzed fusion (**μCF** method) [7, 8].

Above four methods were compared with each other in terms of the transmutation energy and the transmutation rate (effective half-life) by using 3-dimensional Monte Carlo codes. ^{137}Cs was chosen as a target **nuclide**. The transmutation energies for ^{137}Cs with the effective half-life of 2 years in the four methods are tabulated in Table 1 together with accelerated **particles,** energies of the particles, particle beam currents and calculation codes which were employed in the calculation.

The transmutation energy was calculated by dividing input energy by the number of transmut ^{137}Cs Generally the number of transmuted fission products is proportional to their cross sections for transmutation reactions and the number of beam particles which contribute to the transmutation.

Therefore, large cross sections and large number of beam particles which need small energy to be created are favorable for the transmutation energy.

As you can see in Table 1, the μCF method gives the least transmutation energy, and the electron method gives the largest among the four methods. The proton method and the spallation method give almost the same transmutation energy under the condition that the effective half-life of ^{137}Cs is 2 years. Note that the transmutation energy depends on target volume as well as transmutation method employed. We change the target volumes to equalize the effective half-lives in the four methods. Therefore, the target volumes #in, the four methods in Table 1, which are not mentioned, differ from each other (see Fig. 1).

The electron method uses the giant resonance of the (γ, n) reaction to transmute fission products. The y-ray is created as bremsstrahlung from electron. However, since the energy spectrum of the y-rays obtained by bremsstrahlung is continuous, ·only a small part of the y-rays contributes to the (y, n) reaction. Furthermore, other reactions such as pair production and Compton scattering contribute largely compared with the (y, n) reaction. Thus, most of the γ-rays are lost in these reactions before the transmutation occurs. Those reasons make the energy balance worse in the electron method. If we can make a high intensity γ-ray with an exact energy where the resonance (γ, n) reaction takes place, the energy balance becomes better [8].

Both the proton method and the spallation neutron method use the spallation reaction. But in the proton method, fission products are hit directly by proton beam, while in the spallation neutron method, they are exposed to neutrons which are produced in Pb target by injecting proton beam. The secondary neutrons are also utilized for transmutation in the proton method,

but most of the fission products are transmuted by protons directly through the **spallation** reaction. For the transmutation ^{137}Cs, the proton method is more favorable than the **spallation** neutron method in terms of the cross **section because the cross section for** the **spallation reaction is larger than that for the (n, y) reaction. However, about 40 neutrons are produced in** Pb **target through the spallation reaction** by one high energy proton, and those **neutrons are used** for the transmutation in the **spallation** neutron method. Therefore, the transmutation energy in the **spallation** neutron method is smaller than that in the proton method despite the small (n, y) cross section of ^{137}Cs.

As for the μCF method, muons are created by injecting 25 **mA** deuteron beam with an energy of 4 **GeV** into a Be target [9]. One muon causes 175 fusions in a deuterium-tritium target with liquid hydrogen density [8, 9], which means that one muon produces 175 neutrons with an energy of 14 MeV. That is the reason for small transmutation energy in the μCF method despite the large input energy to the deuteron beam.

We will discuss the energy balance. We estimate the energy which we can use for transmutation of ^{137}Cs to achieve the energy balance. Fission yield of ^{137}Cs is 6%. Released energy during one fission event is about 200 MeV. Suppose thermal to electrical conversion efficiency is 33 %, then the electrical energy produced during one ^{137}Cs generation is 1100 MeV, which is calculated by (200 MeV/0.06)x0.33. Thus the transmutation energy for ^{137}Cs should not be more than 1100 MeV. If we use more energy than this energy **to transmute one** ^{137}Cs, **we do not actually transmute but produce** ^{137}Cs, **assuming that transmutation devices are operated by using the energy generated by fission reactors. Actually we should use much less than this energy in order to gain public acceptance for the transmutation. So if it is**

assumed, for example, that the only 10 % of 1100 MeV energy can be used for transmutation of one ^{137}Cs, the upper limit of electrical energy available for the transmutation is 110 MeV. All the transmutation energies in Table 1 are beyond this energy even in the µCF method. Hence it seems that the transmutation by accelerator is difficult to meet the energy balance criterion.

In Fig. 1, effective half-lives of ^{137}Cs in the four methods are shown as a function of the target volume. This figure indicates that the effective half-life increases with increasing target volume. This is because the increase of the target volume is greater than that of the number of transmutation reactions. The effective half-life depends on the conditions such as beam energy and beam current. However, according to various papers on the transmutation by accelerator [3-9] and also this result, we might say that the order of the effective half-life of ^{1}37CS is in several years.

3. TRANSMUTATION BY FISSION REACTOR

Fission reactors for transmutation are also studied at PNC. We have studied the transmutation of ^{137}Cs in fission reactors which we call transmutation reactors [10, 11]. Although the transmutation reactor that we have studied is a high flux fast reactor, fast neutrons generated in the fuel region are thermalized and the thermalized neutrons are used to transmute ^{137}Cs. This is because the neutron capture cross section of ^{137}Cs is approximately one order of magnitude larger for thermal neutron than for fast neutron.

The transmutation reactor is schematically shown in Fig. 2. The cylindrical configuration is taken, and the outer diameter and the height are equal in order to minimize the leakage of neutrons. The Cs region is inside the core, and it is surrounded by the fuel and the reflector. Between the Cs

region and the fuel region, the Be region and the B_4C region are placed as shown in Fig. 2. The beryllium is used as a moderator, while the B4C region is placed to prevent the thermalized neutrons that cause the power peaking from going back to the fuel region.

In the Cs region, ^{137}Cs is loaded in the chemical form of the deuteroxide ^{137}CsOD because the density ϲ of this form is larger than that of metallic form ^{137}Cs, and furthermore the deuterium D as well as Be plays a role as moderator. For simplicity, it is assumed that the purified ^{137}Cs is loaded and ^{137}CsOD is in a molten state which allows it to be continuously reprocessed.

Among some solid fuels, the metallic fuel was chosen for the transmutation reactor because the metallic fuel gives cycle length extension and burnup reactivity reduction [12].

We have investigated what neutron flux level and transmutation rate are achieved under the conditions of ordinary fast reactor such as burnup reactivity and peaking factor.. The constraints of the burnup reactivity and the peaking factor were chosen within 3 %Δk/kk' and 1.7, respectively. The total power is fixed to be 3.5 GW$_{th}$ that is about the same power of an industrialized fast reactor.

We defined the transmutation rate as [11]

$$F = \lambda + \sqrt{\frac{\pi T_0}{4T}} \sigma_{th} \phi_{th} - w/N, \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (1)$$

where

λ : natural decay constant of ^{137}Cs,

σ_{th} : thermal neutron capture cross section of ^{137}Cs (0.25 b),

ϕ_{th} : average thermal neutron flux in Cs region,

w : quantity of ^{137}CS produced in transmutation reactor in unit time,

N : quantity of ^{137}Cs loaded in transmutation reactor,

$$\sqrt{\frac{\pi T_0}{4T}}$$: factor for Doppler effect,

To : room temperature (293.61°K),

T : temperature in Cs region (500°K).

This equation is derived from dividing the quantity of ^{137}CS transmuted in unit time by the quantity of loaded ^{137}Cs, where the quantity of ^{137}Cs produced in the transmutation reactor is taken into account.

With the constraints on the burnup reactivity and the peaking factor mentioned above, we carried out the neutronic calculation, and optimized the transmutation rate. Table 2 summarizes the optimized design parameters and the core performance characteristic of the transmutation reactor. The average thermal neutron flux of 2.5x 10^5 n/c $m^2 \cdot s$ is obtained in the Cs region with the volume of 2.0×10^6 c m^3. The transmutation rate is 2.8 %/year, which is only 1.2 times higher than the natural decay rate. The reason of the low transmutation rate comes from the small neutron capture cross section of ^{137}Cs. The results indicate the difficulty of effective transmutation of ^{137}Cs only by fission reactor under the conditions of ordinary fast reactor. It seems that an innovative core with a special fuel such as particle fuel and liquid fuel which could achieve high power density is necessary to transmute ^{137}Cs efficiently [13, 14].

4. NEW TRANSMUTATION METHODS

It seems that the transmutation methods by accelerator and by fission reactor which have been studied so far have difficulty in satisfying the requirements for the transmutation rate and the transmutation energy

simultaneously. So we have been also studying new transmutation methods which might achieve both high transmutation rate and small transmutation energy at the same time. We introduce moving target method first and then inertial transmutation method.

4.1 **Moving target** method

Moving target method is based on the resonant neutron capture of fission products. Neutron capture cross sections of fission products generally have resonance regions at certain energies and some of them present large values at some resonance energies. Fig. 3 shows the neutron capture cross section of ^{99}Tc [15]. It can be seen that there is a very sharp resonance peak at neutron energy of about 5.6 eV. The maximum peak is about 7000 b. If a strong beam of neutrons with this energy can be produced, a high transmutation rate might be expected. But it is difficult to produce a **monochromatic or a highly controlled neutron beam.**

Instead of accelerating neutrons, we accelerate the target nuclei to have the resonance reaction with thermal neutrons in the moving target method [16]. Since the total **momentum is conserved in any coordinate** system without external forces, the neutron energy can be controlled in a relative manner to match the resonance peak in the laboratory frame where target **nucleus stands still. The concept is illustrated in Fig. 4. Physical phenomena do not depend on inertial frames. If the resonance reaction of the target with neutron is observed in the target rest frame, it can be also observed in the neutron rest frame. The only difference is the resonance energy of neutron capture observed in the two frames. The resonance energy, E_{res}, in the target rest frame is observed as**

$$E'_{res} = \frac{M}{m} E_{res} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

in the neutron rest frame, where m is neutron mass and M is the mass of the target nucleus. In the case of ^{99}Tc, the **resonance neutron capture takes place** at neutron energy of about 5.6 **eV** in the target (^{99}Tc) rest frame, which is converted to target energy of about 550 **keV** in the neutron rest frame. In other words, ^{99}Tc must be accelerated to the energy of 550 **keV** to have the resonance reaction with thermal neutron.

Transmutation device in the moving target method is shown in Fig. 5. Target FP atoms are ionized and are accelerated to the resonance energy, and then they are circulated in a magnetic field. However, if each FP atom is ionized, only a small number of FP atoms can be circulated in a realistic magnetic field due to the. repulsive electric force between the FP atoms. But **it** is necessary to circulate a large number of FP atoms in order to transmute fission products in large quantities. Therefore, **microparticles** made of FP atoms, which we call matrons, are circulated instead of individual FP atoms. Matrons are produced and are charged in a matron source [17, **18].** After the distribution of particle size is controlled, the matrons are accelerated and are circulated in the magnetic field. During the circulation, the matrons are exposed to the thermal neutrons which are produced by fission reactor or accelerator, and the resonance reactions are brought about.

Parameters of the device for the transmutation of ^{99}Tc are summarized in Table 3. The matron radius is 0.01 **μm.** The each matron contains 2.93x105 atoms, and its charge number is 293, which means that one atom per 1000 atoms is charged. One matron can be circulated with the radius of 3.4 m under the magnetic field of 10 T. However, the target of 0.5 **mol** (-1018 matrons) must be circulated for about 14 hours to achieve an effective

transmutation [16]. This poses a rather tough confinement problem. Although confining the matrons with 0.5 **mol** atoms is easier than confining the same number of ionized atoms, the confinement force has to be still very strong. Hence, neutralization **of** matron charge by electrons is needed to reduce the confinement force.

The device can transmute an amount of ^{99}Tc produced by a fission reactor of 1 GW$_e$ with an effective half-life of 14 hours. Note that the natural half-life of ^{99}Tc is 2.1×10^5 years. This moving target method provides high transmutation rate. But further studies such as effective confinement of matrons .**are still** necessary to optimize the device.

4.2 Inertial transmutation method

Another new approach we are studying is to utilize inertial confinement fusion **(ICF)**. 'In this method, fission products are placed outside the **deuterium(D)-tritium(T)** core, forming FP shell as can be seen in Fig. 6 [19, 20]. They are compressed together with the DT core by laser or particle beam, and are irradiated by 14 **MeV** neutrons produced by DT fusion inside the pellet.

Fission products are transmuted **mainly through (n, 2n) reaction. For** ^{90}Sr and ^{137}**Cs,** (n, 2n) cross sections **at neutron energy of 14 MeV are 100** and 10 times, respectively, larger than (n, **γ**) cross sections at thermal neutron energy. Therefore, the (n, 2n) reaction is more favorable than the (n, y) reaction for transmutation of such **nuclides** which **have small neutron** capture cross sections. Furthermore, compressing the **FP shell leads to the** enhancement of (n, 2n) reaction due to high density. **As a result, a high transmutation rate can be expected in this method.**

A simple calculation indicates the enhancement of the reaction. Suppose that a neutron with energy of 14 MeV is produced in the center of the **DT core, the probability P_0 that the neutron reacts with FP in the FP shell is given as**

$$P_0 = 1 - \exp(-n\sigma d). \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

Here n, σ and d are defined as number density of the FP, (n, 2n) cross section of the FP, and thickness of the FP shell, respectively. Since the (n, 2n) reaction is dominant in this case and the thickness of the FP shell is very thin (the order of 100 pm), multiple scattering of neutron and (n, y) reaction are neglected in the calculation of the reaction probability. We have confirmed the validity of our treatment by a Monte Carlo code. If the pellet is compressed with a ratio of. K, the number density n becomes K times larger than that before compression and the thickness d becomes $d/K^{1/3}$, which leads eq. (3) to

$$P = 1 - \exp(-K^{2/3}n\sigma d). \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (4)$$

In the field of ICF, the compression ratio of 1000 is usually considered to achieve the breakeven [21]. So we use K= 1000 hereafter. We assume that the FP is ^{90}Sr and the thickness of FP shell is 500 μm, then, using n=1 .7x 1022cm-3 and σ=1 .7b, we can calculate the ratio of the reaction probability y after compression to that before as

$$\frac{P}{P_0} \cong 93. \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

Thus we might obtain a high transmutation rate in this inertial transmutation method.

We define the transmutation rate as a transmutation probability of FP in one implosion by shot [19]. Fig. 7 shows the transmutation rate of ^{90}Sr as a function of the radius of DT region (DT core) in the cases of the thickness of Sr region (FP shell) d=100, 500 and 1000 pm. In this calculation, the compression ratio of 1000 in both the regions (DT region and Sr region) and the number density of solid DT ($n_{DT}=4.7\times10^{22}cm^{-3}$) are used. The transmutation rate increases with increasing radius of DT region because of the increase of neutron yield which is proportional to the volume of DT region. When the DT region radius is fixed, the transmutation rate is decreased as the thickness of Sr region is increased. This is because the **volume of Sr region increases rapidly with the thickness d** compared with the increase of the reaction probability P.

Transmutation energy for ^{90}Sr is shown in **Fig. 8 as a** function of the thickness of Sr region. This calculation is based on a simple statistical model discussed in refs. 19 and 20. It is assumed that the temperature of DT region after compression is 10 **keV** which is demanded in order to get the energy gain by the inertial confinement fusion [22]. The temperature of Sr region is determined to be 1.7 **keV** from the assumption of pressure balance between the DT region and the Sr region after compression [19]. In this calculation, we neglect the conversion efficiencies from input energy to laser or particle beam energy and from the laser or the particle beam energy to the internal energy of pellet. We also neglect the effect of a-heating [23]. Taking account of those conversion efficiencies makes the transmutation energy larger, while the effect of a -heating will reduce it. At the stage of neglecting them,

the **inertial transmutation method satisfies the requirement of small transmutation energy as well as high transmutation rate.**

It is difficult to transmute all the fission products in the pellet by one shot. **The FP nuclei which remain after the shot are collected and are re-fabricated for further shot. We estimated the number of the cycles to transmute the amount of FP in one pellet. Fig. 9 shows the relation between the number of cycles and the pellet radius for** ^{90}Sr. **The result indicates that a small pellet needs a large number of cycles. In order to reduce the number of cycles, the pellet radius has to be large. However, a large pellet needs a strong laser or particle beam to compress. It is necessary to investigate the possibility of compression of the large pellet.**

The inertial transmutation method is attractive because of not only its uniqueness of approach (for example, it incorporates the effect of compression) but also the. high transmutation rate and the possibility of small transmutation energy. But this method is in a preliminary study phase, and much studies are needed to establish this method as an effective transmutation method for long-lived fission products.

5. SUMMARY

Studies on transmutation of fission products at PNC have been **discussed. Four** transmutation methods by accelerators were compared in **terms of transmutation energy and effective half-life for** ^{137}Cs. **It was found from this comparison that the transmutation energy was the least in the μC F method and the largest in the electron method among the four methods discussed here. But the difficulty in constructing the transmutation** devices for these methods may be the opposite, namely, the device in the μC F method may be the most difficult to be constructed. **As** for effective half-

lives of ^{137}Cs in the four methods, all of them were calculated to be in the order of several years.

Concept of the transmutation reactor was described. **It was shown** that the transmutation reactor optimized under the conditions of burnup reactivity within 3 **%Δk/kk'** and the peaking factor within 1.7 gave the average thermal neutron flux of 2.5x1015 **n/cm^2·s** in the **Cs** region and the transmutation rate of 2.8 %/year in the case of the transmutation of ^{137}Cs. The low transmutation rate is due to the small neutron capture cross section of ^{137}Cs. **More effective transmutation might be expected if the transmutation reactor is applied to the transmutation of other fission products such as** ^{99}Tc **and** ^{129}I **which have larger neutron capture cross sections than** ^{137}Cs.

Two new transmutation methods were introduced. One was the moving target method, and the other was the inertial transmutation method. The moving target method uses the resonance reaction between fission product and neutron. In this method, matrons made of FP atoms, instead of the neutrons, are accelerated to have the resonance reaction with thermal neutrons. A device of this method was described and parameters of the matron were also shown. Confinement of the matrons is a serious problem. In general, the resonance reaction has a large cross section. Hence the moving target method gives a very high transmutation rate. But this concept is quite new and much investigation is yet to be done.

On the other hand, the inertial transmutation method utilizes the inertial confinement fusion. In this method, a pellet which contains fission products is compressed, and the fission products are transmuted by high energy neutrons produced by the DT fusion inside the pellet mainly through (n, 2n) reaction. It was found that this method as well as the moving target

method gave a high transmutation rate. The reasons are that the neutron flux is very high because of a small pellet size and a short implosion time, the cross section for the (n, 2n) reaction is large compared with the cross section for the (n, γ) reaction, and the compression of the transmutation pellet enhances the neutron reaction probability. The transmutation energy was calculated by using a simple statistical model and neglecting the conversion efficiencies and the effect of a-heating. The calculation result indicated that the small transmutation energy was obtained in the inertial transmutation method. The number of cycles to recover and re-fabricate the pellet was also discussed in order to transmute all the fission products in one pellet. We studied the number of cycles in the case of ^{90}Sr. It turned out that a large pellet reduced the number of cycles.

Concerning the moving target method and the inertial transmutation method, they have a potential to satisfy both high transmutation rate and small transmutation energy at. the same time. But they are in a preliminary study phase, and much studies are necessary to establish both methods.

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Table 1
Transmutation Energy for ^{137}Cs

Effective half-life : 2 years
Target : cylinder

Transmutation method	Accelerated particle	Energy [MeV]	Current [mA]	Calculation code	Transmutation energy [MeV]
Electron method	e-	100	2000	EGS4	4700
Proton method	p	500	900	NMTC	570
Spallation neutron method	p	1500	300	NMTC+MCNP	510
μCF method	d	4000	25	MCNP	200

Table 2
Design Parameters and Core Performance Characteristic of the
Transmutation Reactor

Reactor power	3.5 GW_{th}
Average power density	500 w/cc
Pu enrichment (inner fuel)	15.0 w/o
Pu enrichment (outer fuel)	10.1 w/o
Core diameter	234.9 cm
Core height	234.9 cm
Core volume	107 cm^3
Cs region diameter	137.4 cm
Cs region height	137.4 cm
Cs region volume	2.0×10^6 cm^3
Volume ratio of Cs region to core	"20 %
Be region thickness '	10.0 cm
B4C region thickness	1.0 cm
Inner fuel region thickness	12.0 cm
Outer fuel region thickness	25.8 cm
Reflector region thickness	40.0 cm
^{137}Cs loading	6610 kg
Amount of transmuted ^{137}Cs (including natural decay)	184.5 kg/year
Transmutation rate	2.8 %/year
Average thermal neutron flux in Cs region	2.5×10^{15} $n/cm^2 \cdot s$
Burnup reactivity	2.85 %Δk/year
Peaking factor	1.7

Table 3

Parameters of Device for Transmutation of ^{99}Tc in the Moving Target Method

Matron Source

Matron Radius	0.01 μm
Number of Atoms in Matron	2.93×10^5
Charge Number	293
Electric Field on Surface	4.2×10^9 V/m
Acceleration Voltage	550 kV
Total Current	**0.682 A**

Storage

Total Amount of Target	**0.5 mol**
Confinement Time	**14 hr**
Thickness of Target	**20 cm**
Matron Density	**3.4×10^{11} cm^{-3}**
Radius of Gyration ‛	**3.4 m (for 10T)**
Length of Target Region.	**70.5 cm (for 10T)**

Neutron Field

Flux	**10^{15} cm^{-2}sec^{-1}**
Energy	**Thermal**
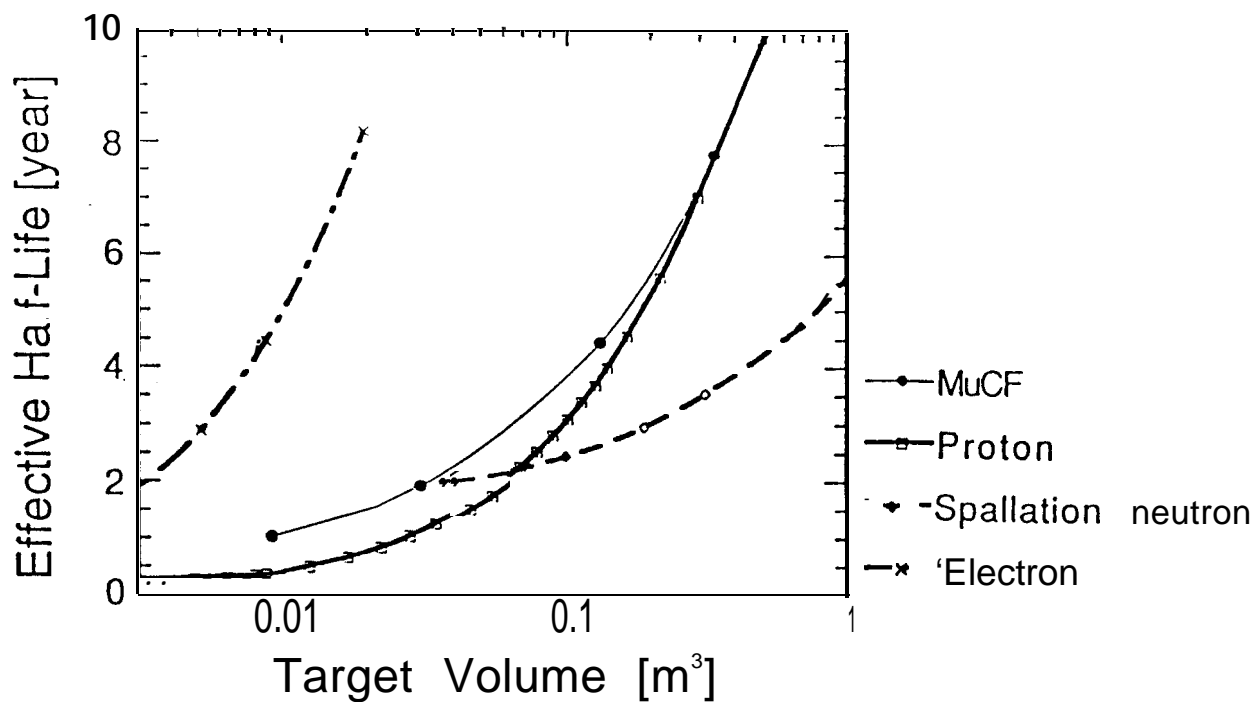
Fig. 1. **Effective Half-Lives of ^{137}Cs in the Four Methods by Accelerators.**
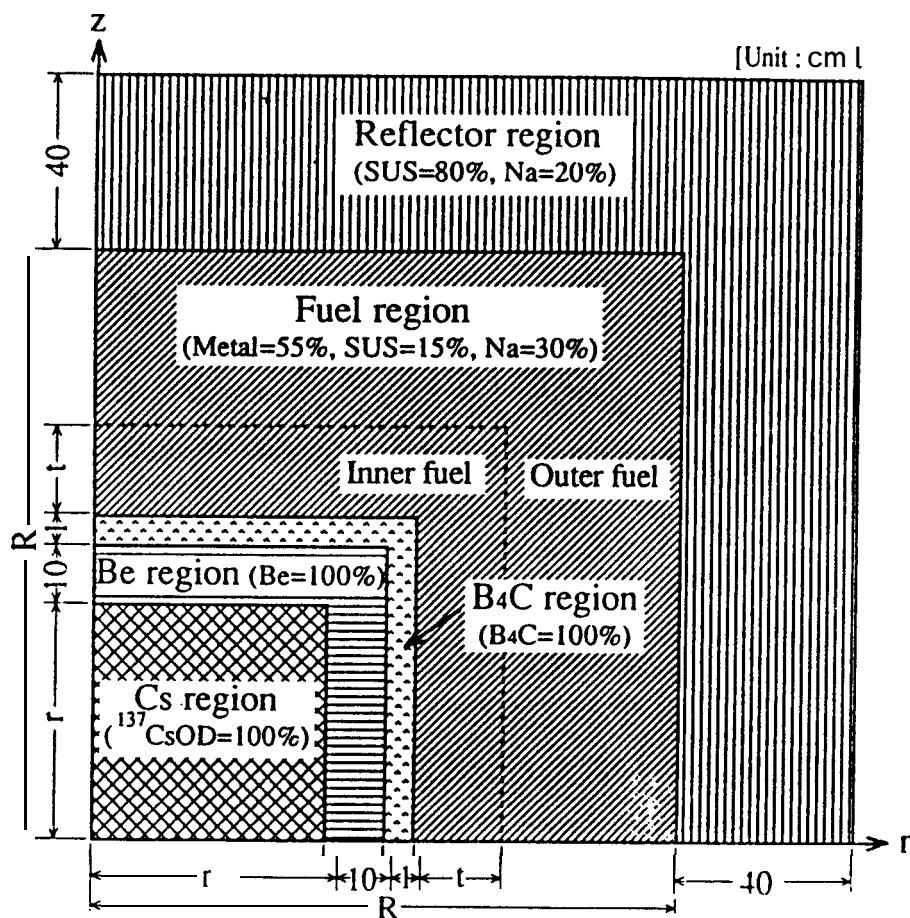
Fig. 2. Core-Reflector Configuration of the Transmutation Reactor.
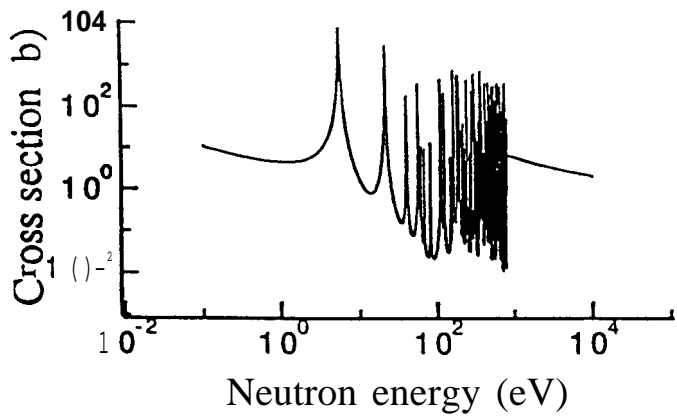
Fig. 3. Neutron Capture Cross Section of ^{99}Tc.

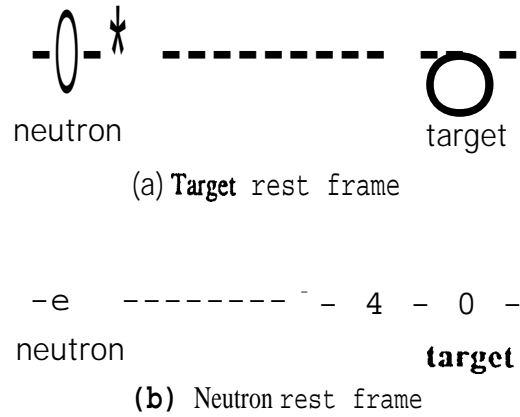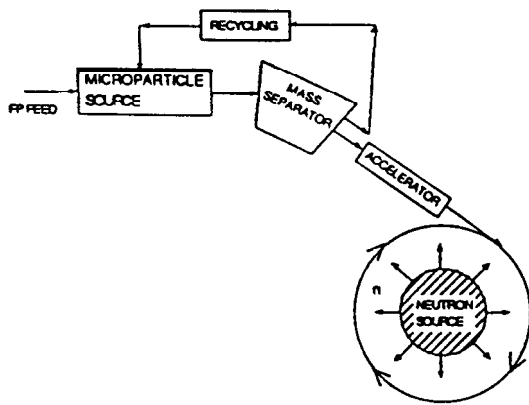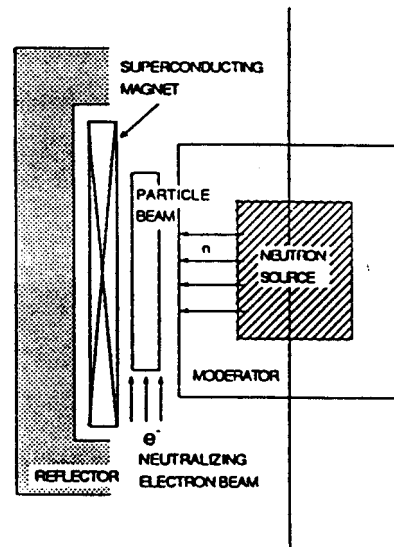(a) Target rest frame

(b) Neutron rest frame

Fig. 4. Concept of Moving Target Method.

(a) total system

(b) reaction vessel
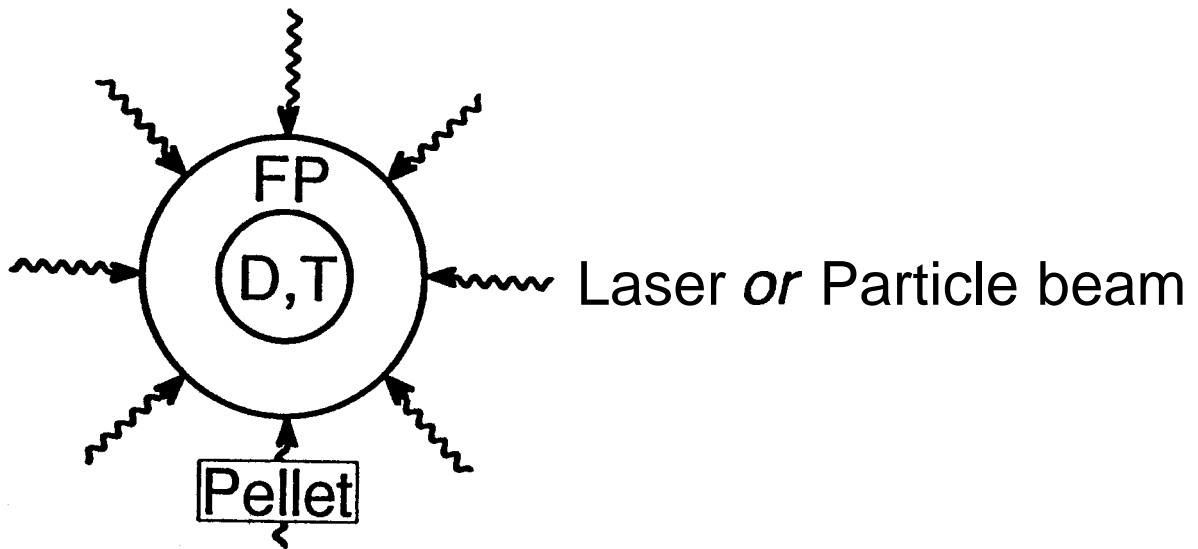
Fig. 5. Transmutation Device in the Moving Target Method.

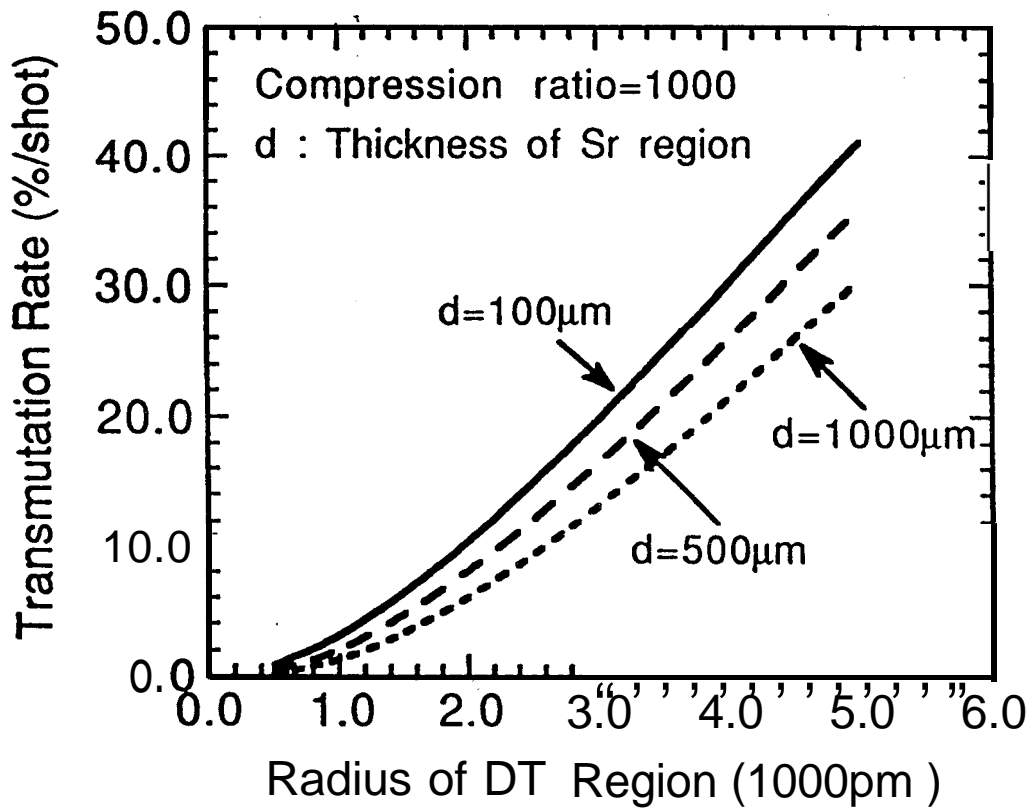Fig. 6. Concept of Inertial Transmutation Method.

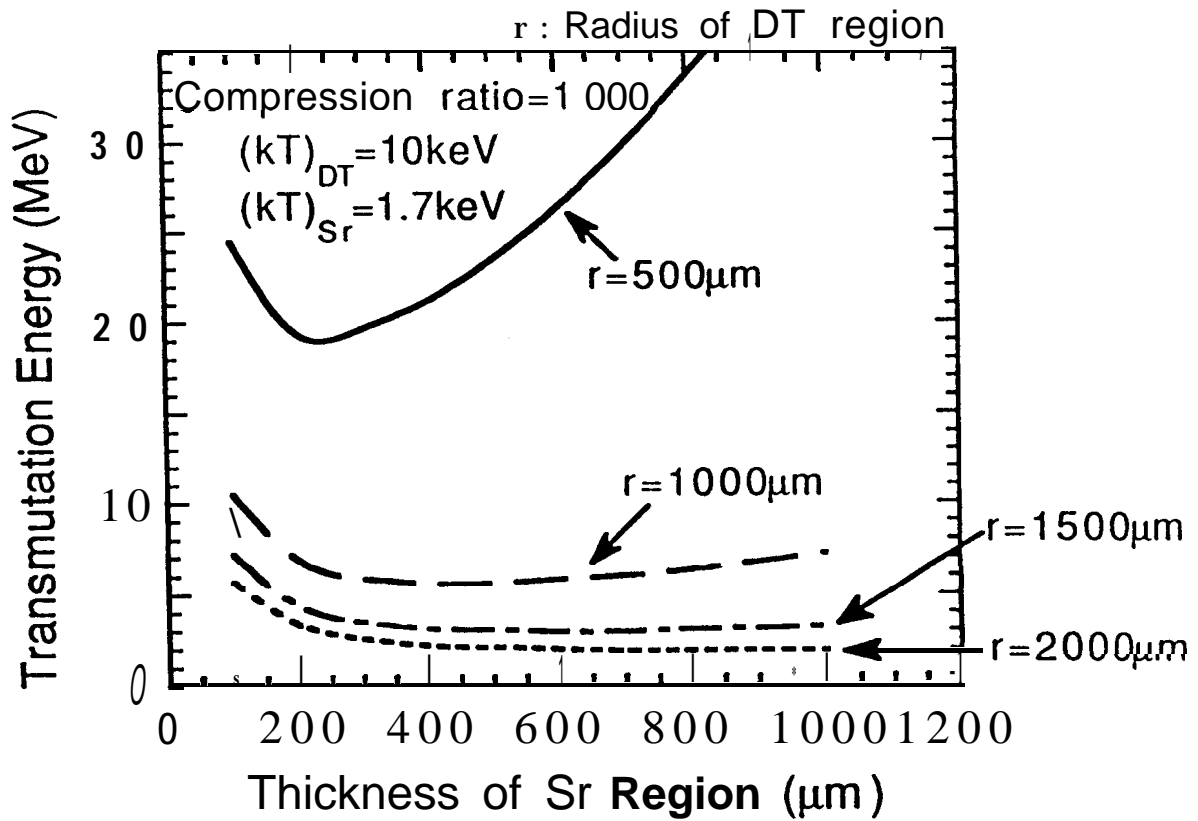Fig. 7. Transmutation Rate in the Inertial Transmutation Method.

r : Radius of DT region

Compression ratio=1 000

$(kT)_{DT}$=10keV

$(kT)_{Sr}$=1.7keV

r=500μm

r=1000μm

r=1500μm

r=2000μm

Fig. 8. Transmutation Energy for ^{90}Sr in the inertial Transmutation Method.

$a = \dfrac{\text{Thickness of Sr region}}{\text{Radius of DT region}}$
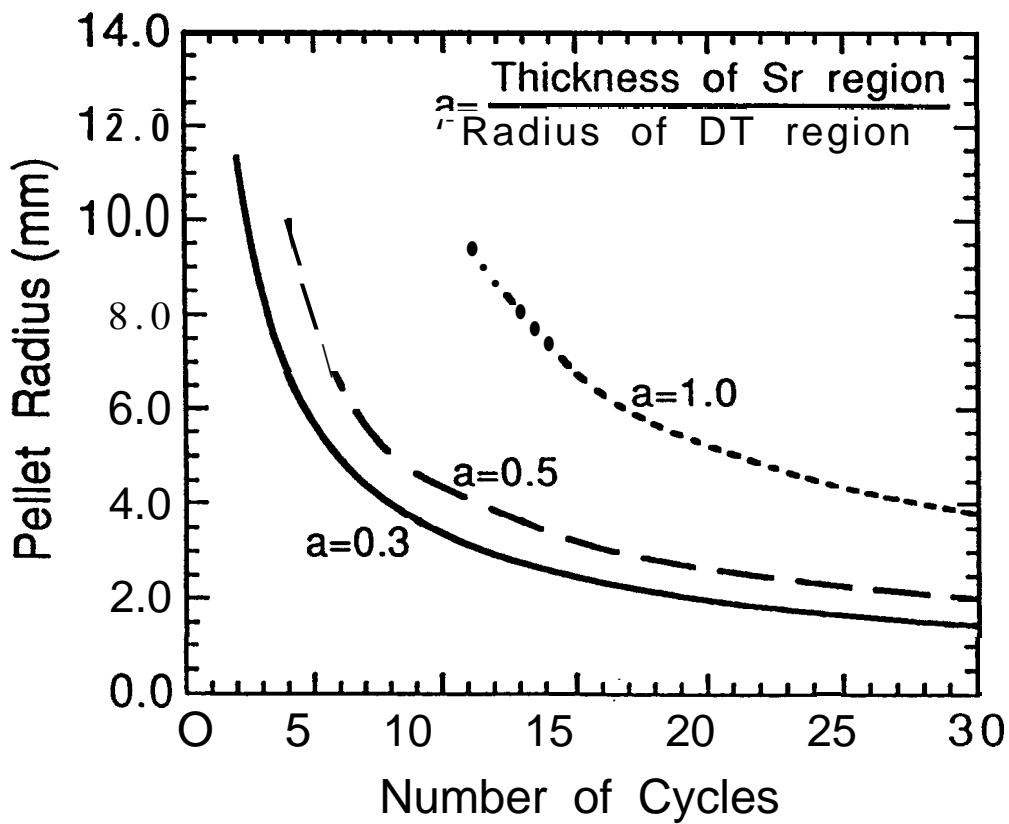
a=1.0

a=0.5

a=0.3

Fig. 9. Relation between Number of Cycles and Pellet Radius for ^{90}Sr.