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USE OF THE LINEAR ACCELERATOR FOR INCINERATING THE FISSION PRODUCTS OF Cs^{137} AND Sr^{90}

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H. Takahashi, N. Mizoo and M. Steinberg
Brookhaven National Laboratory
Upton, New York 11973

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ABSTRACT

Transmutation of fission products Cs^{137} and Sr^{90} using the neutron produced by high energy proton collision with heavy nuclei were investigated. Because of the small thermal neutron cross section for (n,γ) reaction of Cs^{137} (0.1 barn), a high neutron flux of 10^{17} n/cm^2 sec is required to transmute Cs^{137} at a rate ten times faster than the natural decay. This range of high flux is attainable in the spallation reaction of high energy proton beam interact with liquid Pb target. The neutronic calculation by using NMTC, HIST3D, EPR, TAPEMAKER and ANISN codes indicates that the spallation neutron can transmute 229 Kg Cs^{137} and 155 Kg Sr^{90} fission products per year (at a rate of 10 and 30 times faster than their natural decay rate) by running a 300 mA, 1.5 GeV proton beam. Thus, if we transmute these fission products, just after a burning cycle, this accelerator can transmute these fission products produced in five or six 1000 MWe power plants.

The heat removal problem from target is alleviated using the liquid lead target, and the average thermal power in the Cs_2O_2 and SrO region are about 55 W/cc, thus this thermal energy can be removed by D_2O coolant without difficulty.

By using a uranium target, we can transmute these fission products about 2 or 3 times more than the case of Pb target. This is due to the fact that the neutron yield from uranium target is increased 3 times more than Pb target. The neutron yields are calculated by including a high energy fission process in the NMTC code and it is shown that the calculated yield is reasonable agreement with Barashenkov's calculation and the thermal energy deposition from this high energy fission is not so large.

When the (n,γ) reaction is used for transmuting Cs^{137} isotope, the necessity of separation of Cs^{137} from other Cs isotopes is discussed. The transmutation of Cs^{137} nuclei using (p,x'n), (n,xn) reactions suggested by Ichimiya is examined by using NMTC code, and it was found that use of this reaction is not an efficient approach transmuting Cs^{137}.

Finally, the hybrid system using transuranic target which is surrounded by $Cs^{137}{}_2O_2$ and $Sr^{90}O$ is suggested and the advantage and disadvantage of using deuteron beam instead of proton beam are discussed.

1. Introduction

Several approaches for transmuting Cs^{137} and Sr^{90} using neutrons produced by fission, fusion and spallation reactions have been proposed.[1],[2],[3],[4] To transmute these fission products, two reactions of (n, γ) and (n,xn) (x>2) can be considered. Only the (n,γ) reaction can be used for the fission neutron. The 14 MeV neutron produced by the (DT) fusion reaction can be used in both methods. The neutron produced by the spallation reaction and the subsequent evaporation reaction from the heavy target nuclei has mainly a lower

energy than the threshold energy for the (n,2n) reaction and can be used for the (n,γ) reaction.

As is well known, the transmutation of Cs^{137} by thermal neutrons is much more difficult than the Sr^{90} because the thermal neutron (n,γ) cross section of Cs^{137} (0.1b) is smaller than the Sr^{90} (0.9b). In order to transmute Cs^{137} at a rate ten times faster than natural decay, high neutron flux of $10^{17} r/cm^2/sec$ is required. This range of high neutron flux is hardly obtainable in a fission reactor, and the flux available in the present advanced high flux reactor is far less than this flux. This is due to the difficulty to removing the heat produced in a fission reactor.

The low energy fission reaction produces 2.5 ~ 3.0 neutrons per fission (ν), and the thermal energy released (Q) is about 200 MeV. Thus the heat deposited per neutron, which can be used for transmuting the fission product, is $(Q/\nu-1)$ = 133 MeV ~ 100 MeV, (where 1 neutron is used for fission chain reaction). To obtain a high thermal neutron flux, Taube[2] has proposed to use a reactor composed of a fast core and a thermal neutron trap.

The D-T fusion reaction, which produces a 14 MeV neutron and a 3.2 MeV α particle, is a neutron rich reaction. This high energy neutron can be used for transmuting Cs^{137} isotope by (n,xn) (where $x>2$) and (n,γ) reactions. Thus this makes the value of Q/n very small. (Where n is the number of neutron which can be used for transmuting fission product isotope). The fusion reactor, however, does not exist as yet. A proof of principle fusion reactions is still to be demonstrated and it is estimated that a commercial fusion reactor may not be available for at least another 30 years.

Another technology for producing neutron is the spallation reaction of high energy charged particle with nuclei. A 1 GeV proton can produce about 35 neutrons by interaction with a lead target. Even if all the energy of the proton is assumed to be deposited in a lead target (actually the deposition energy is lower than the injected particle energy, the value of Q/n = 28.6 MeV which is much smaller than that of the fission reaction. This value of Q/n is a function of space and we can make this value much smaller in the front part of a target by suitable design of the target. This is the advantage of using a spallation neutron source compared to a fission neutron source.

For the last three years, a group at Brookhaven National Laboratory[5] has studied the linear accelerator reactor as a fuel enricher generator (LAFER). Since non-reprocessing of fuel was emphasized in this program, our design study was rather conservative. Despite this constraint, it was found that this regenerator could provide fuel for three 1000 MWe light water reactor with a 1.5 GeV 300 mA beam power (= 450 MW) proton accelerator. Applying the regenerator in this manner would extend the natural resource by a factor of 3.6. The resulting cost of electricity is estimated to increase by only 35% over the present LWR system, comparable to projected breeder costs.

In the present paper, we discuss the transmutation of Cs^{137} and Sr^{90} by using the same spallation reaction to produce the neutrons as in design which utilizes flowing liquid lead as the primary target. In section 2, the neutronic problem and energy deposition for transmuting Cs^{137} and Sr^{90} will be discussed. In section 3, the necessity for chemical separation and isotope separation which are required for transmuting Cs and Sr isotope will be discussed. In section 4, the possible increase of neutron yield and the problem of heat deposition in the uranium target will be studied and compared to the lead target. In section 5 the direct transmutation of Cs^{137} spallation and the evaporation reaction which was suggested by Ichimiya will be discussed. In section 6, other possibilities of incinerating transuranium products and using deutrons instead of protons will be mentioned.

2. Neutronic Study and Heat Removal

Two essential factors in the incineration of fission products are transmutation rate, Tr, and the number of isotopes transmuted by 1 proton. The transmutation rate is defined as the number of isotopes transmuted in a unit of time (sec) and is expressed as

$$Tr = \int \sigma_a(E)\, \Phi(\underline{r},E)dE \qquad (1)$$

where $\sigma_a(E)$ is the transmuting cross section such as $\sigma_{n,\gamma}(E)$ and $\sigma_{n,xn}(E)$. $\Phi(\underline{r},E)$ is the neutron flux. To calculate this flux, a computer code system consisting of five main programs; NMTC,[6] HIST3D, EPR[7] TAPEMAKER, ANISN,[10] is used. The NMTC is used to calculate the spallation and evaporation reactions above 15 MeV by the Monte Carlo method. Collision events of neutron slowed down below 15 MeV are determined by NMTC.[6] The collision events file is analyzed with HIST3D to obtain neutron distribution which are used as the neutron source in the transport calculations for neutrons in the energy below 15 MeV. The EPR [7] neutron cross section is based on ENDF/B-IV,[8] and the cross sections for Cs^{137} and Sr^{90} are taken from the data compiled by AAEC/E214.[9] In this survey calculation, the simple slab geometry instead of a rectangular geometry, is used to calculate the many cases by changing parameters. The spallation evaporation neutron yield (N_p) and its distribution for a high energy proton injection is calculated by NMTC. The neutron flux distribution $\Phi(r,E)$ under 15 MeV energy which is normalized to a one neutron source is obtained by the ANISN calculation.[10]

The neutron flux $\Phi(r,E)$ for an I_p proton beam current is expressed

$$\Phi(r,E) = \Phi(r,E)\, N_p \cdot I_p \cdot P_a \qquad (2)$$

where P_a is the number of protons in 1 ampere of beam current (6.24×10^{18}).

The number of isotope atoms transmuted by 1 proton (Tn) is expressed by

$$Tn = \iint \Sigma_a(N,E)\Phi(r,E)drdE.Np \qquad (3)$$

where $\Sigma_a(r,E) = N(r)T_a(E)$

where N is the number of fission product isotopes.

The factor Tn is closely related to the evaluation of the energy balance for each transmutation process. To produce a proton with energy of E_p MeV, an electric energy E_e MeV is required. To produce the electric energy E_e, the thermal energy Eth is needed. They are expressed by

$$E_e = E_p/N_b \qquad (4)$$

$$E_{th} = E_e/N_{th} = E_p/N_{th}\ N_b \qquad (5)$$

where N_b is the conversion efficiency from electric energy to beam energy. N_{th} is the thermal efficiency of converting thermal energy to electric energy. For this calculation the values of 50% and 33% are taken respectively for N_b and N_{th}.

To generate E_{th} in a fission reaction, the amount of fission product Y of yield f_y generated is

$$Y = \frac{E_{th}}{E_{fission}} \quad fy = \frac{E_p \quad f_y}{E_{fission}\ N_b\ N_{th}} \qquad (6)$$

where $E_{fission}$ is the energy released by the fission reaction and amounts to 200 MeV.

In the case of transmuting Sr^{90} and/or Cs^{137} with a 1.5 GeV proton beam, $E_p = 1.5x10^3$ MeV and $f_y \sim 0.06$, then the amount of fission product Y of Sr^{90} and/or Cs^{137} to produce a 1.5 GeV proton is calculated as

$$Y = \frac{1500}{200} \times \frac{0.06}{0.5x0.33} = 2.7 \qquad (7)$$

Hence, the factor Tn should be much greater than 2.7 in order for the process to be an effective transmutation system.

In addition to the above two factors, total loading mass W, and the amount of transmutation per year, Tw, are also calculated for SrO and Cs_2O_2. The factors W and Tw can be expressed as,

$$W = \rho v \qquad (8)$$

$$Tw = Tn.Pa.y \cdot \frac{1}{Av} \cdot M(SrO)$$

or

$$= Tn.Pa.y \cdot \frac{1}{Av} \cdot \frac{M}{2} (Cs_2O_2) \qquad (9)$$

where,

v : volume of SrO or Cs_2O_2
ρ : densities of SrO or Cs_2O_2
y : a year in sec. unit (3.15×10^7)
Av : Avogadro's number (0.6023×10^{24})
M : formula weight of SrO or Cs_2O_2

One of the aims of this study is to search for a transmutation system being large Tr and Tn values, and also with realistic values of W and Tw. Calculations were carried out for a one dimensional slab geometry and are shown in Figures 1 and 2. The neutron yield, Np, for the injection of a 1.5 GeV proton into a Pb slab target is calculated to be 44.4.

The effective incineration of Cs^{137} is increased in the case where the region of Cs^{137} is placed in closer proximity to the liquid lead target than the Sr^{90}. Table I shows the values of Tr and Tn in the case of the configuration shown in Figure 1. The system has two homogeneous transmuting regions with 50cm widths, one of which contains Cs_2O_2 and the other SrO. The volume fraction v/o of Cs_2O_2 is varied from 10% to 80%.

The factor Tr in the case of 10% volume fraction of Cs_2O_2 is 1.5×10^{-8} sec (20.5λ) while Tn is as little as 7.68 nuclei/proton. It should also be noted that almost one-half of the neutrons are captured or leaked out axially at the Pb target region.

The volume fraction v/o of Cs_2O_2 is, then, increased in order to increase Tn and to decrease neutron loss in Pb region. Value of Tn is increased to 25.0, while Tr is decreased to 8.4λ for the system, which contains 80 v/o of Cs_2O_2. The amount of neutron loss in the Pb target region is decreased to 0.24. Table II shows the case of changing the width of Cs_2O_2 region with 80 v/o of Cs_2O_2 in D_2O. These tables indicate that in case of the low volume fraction of Cs_2O_2 in D_2O, a large fraction of source neutrons is lost by capture in the lead target.

If the solid strontium region is placed in the Pb target, some of the neutron loss in the lead target can be saved by the higher cross section of Sr^{90} than Cs^{137}. Table III shows the Tr and Tn values for the system shown in Figure 2, however, a much larger amount of Sr^{90} is incinerated than the Cs^{137} in this case. From this study, the system shown in the last column of Table II is best for incinerating the Cs^{137} and Sr^{90}. The total amounts of initial inventory of Cs^{137} and Sr^{90} are 2150 Kg and 470 Kg and the amount of the transmutation of these fission products per year are respectively 229 Kg and 155 Kg which correspond to the transmutation rate of 10 and 30 times faster than their natural decays.

Figure 3 shows the flux distribution for the case of Figure 1. In this study, a 1.5 GeV, 300 mA proton beam is used for producing neutrons by spallation of a lead target. About 10% of the total power, 450 MW, is carried out of the target region by the emitted neutron. The remaining 90% of the energy is disipated in the target region by ionization loss of charged particle. The largest part of heat developed by beam energy occurs near the end of the range of the proton beam. The range of 1.5 GeV proton in the solid lead is about 90cm, and the high neutron yield is in the front part of target, while the heat is mainly generated towards the end of the target. Thus a high intensity of neutron flux can be obtained in the region separated from the heat source. This makes the heat removal from target easier. By using liquid Pb, the heat depositions can be rather easily removed from the target region.

The heat deposition in the fission product regions of Cs_2O_2 and SrO is mostly due to the (n,γ) reaction. Even, it is assumed that all the energy of about 8 MeV is produced by an (n,γ) reaction is deposited in the Cs_2O_2 element. In the case when a half of neutron yield is assumed to be captured in Cs_2O_2, the total heat production in Cs_2O_2 region is about 53 MW where 22 is half of N_p and 8 MeV is the neutron

$$\frac{22 \times 8 \text{ MeV}}{1500 \text{ MeV}} \times 450 \text{ MW} = 53 \text{ MW}$$

binding energy and the average power of $Cs^{137}{}_2O_2$ is 53 W/cc, it is not difficult to remove this amount of heat by D_2O coolant. The region for SrO is also the same as in the case of Cs_2O_2.

3. Use of Uranium as Target Material

The neutron yield from lead is not excessively large, the 450 MW beam can transmute the fission product produced by only 5 ~ 6 1000 MWe nuclear power plant, if the incineration is carried out for the fission product soon after burning cycles.

To increase the incineration number for fission product, Tn, use of a U^{238} instead of liquid lead should be considered. The neutron yield from a large block of natural uranium by 1 GeV proton injection has been estimated as 100 by Barashenkov.[11] The authors calculated the yield as 112 ± 10 by including the fission process into the NMTC code.[6] The detail of the neutron yield is shown in Table IV. This value results in increasing of Tn about 3 times for the case of a liquid lead target.[12] It has been considered, however, that one difficulty in using a uranium target is the removal of heat deposited by the fission reaction. The total kinetic energy of two fission fragments is about 160 MeV, regardless of lower or higher energy fission. This energy is deposited near the place where the fission occurs. On the other hand, the numbers of neutrons produced by fission (ν) increases from 2.5 for 1 MeV neutron fission to 12.5 for 300 MeV proton fission.[12] This makes value for (Q/n) in high energy fission small. Recent experimental results show[13] that the

ratio of heat deposition to neutron yield for a uranium is almost the same as for lead. Thus, the heat deposited in a uranium target might not be so different from the lead target in the case when the same number of neutron yield is required.

One of the problems using uranium material as a target is the much higher melting point of this material than lead. Although the molten salt of uranium has a low melting point, it contains a small concentration of uranium elements, so that the neutron yield for this material is rather small. Thus the uranium compound which has a high concentration of uranium, low melting and low vapor pressure, should be utilized to alleviate the problems of heat removal and the need for a window. Table IV also shows that the neutron yield from 50% U, 50% Na is almost the same as for uranium.[12] The metal uranium cooled by sodium might be used as a target, however, a window must be provided in this case.

When fission occurs, additional fission products of Cs^{137} and Sr^{90} are produced. The number of Cs^{137} and Sr^{90} produced per unit neutron yield, depends on the ν value and the yield of these elements. The distribution of fission products yield depends on the fission excitation energy in fission reaction.[13] Figure 4 shows the experimental mass distribution for the case of a 300 MeV proton fissioning U^{238} fission. This distribution has a shape of flat top mountain. It is different from the one for the lower energy U^{238} fission, where the distribution is a two peaked one with deep valley between them.

In Figure 4, the mass distribution calculated by Fong's statistical fission model and using both Janeck, Gravey and Kelson's and Fong's mass formulae are shown. These are the two peaked distribution with shallow valley and do not reproduce the experimental results. The theory should be refined to solve this discrepancy. Furthermore, when Pb and/or Uranium is used as a target, the spallation product which has a long half life should be studied, in addition to the Cs^{137} and Sr^{90} isotope from the fission reaction.

4. Isotope Separation of Cs^{137} From The Cs Fission Products

When the (n,γ) reaction is used for transmuting the Cs^{137} isotope, the Cs^{133} and Cs^{135} should be removed from Cs fission product by isotope separation.

These two isotopes have larger thermal neutron capture cross sections than the one for the Cs^{137} isotope as shown in Table V. If we burn the Cs^{137} together with these two isotopes, a large part of the neutrons are captured by the two isotopes and only small amounts of the Cs^{137} isotope can be transmuted because of the very small thermal (n,γ) cross section of Cs^{137}. Furthermore, the Cs^{134} produced from Cs^{133} has a very long life time (2,060 years) and has a large capture cross section (144.89 barn). Thus, Cs^{134} can also consume another neutron. The Cs^{136} produced from Cs^{135} decays to Ba^{136} with a half-life of 13

days, this Ba^{136} isotope (stable) has a rather large thermal neutron capture cross section (6.3358 b). If Ba^{136} isotopes are not removed by chemical separation, this isotope also consumes a neutron. Thus, in order to incinerate one Cs^{137} fission product, two or more neutrons are consumed by the other isotopes. This may be very uneconomical. Thus the Cs^{137} isotope should be separated from Cs^{133} and Cs^{135} isotopes, before being put into the thermal neutron incinerator.

The neutron capture product Cs^{138} from Cs^{137} decays to Ba^{138} with a half life of 2.9 min. As shown in Table VI, the Ba^{138} has a larger capture cross section of 0.35 barn compared to Cs^{137} and the parasitic neutron capture will be increased, if the chemical separation of Ba^{133} from $Cs^{137}{}_2O_2$ assembly is not carried out repeatedly. In the case when the transmutation rate, Tr, is about 10 times faster than natural decay (effective half life 3 years), chemical separation should be performed at yearly intervals.

On the other hand, in the case of the strontium fusion product waste Sr^{88} (stable) and Sr^{89} (51 day) are produced together with the 30 year half-life Sr^{90} isotope in the fission reaction. The yields are respectively 3.57% and 4.79%. The isotope Sr^{89} is decayed to Y^{89} rather quickly, so that we can separate this out by chemical processing. The stable isotope Sr^{88} has a much smaller thermal neutron capture cross section (6.03×10^{-3} b) than the Sr^{90} (0.9 barn). Therefore, it is not necessary to separate the Sr^{90} isotope from the Sr element.

5. Incineration of Cs^{137} By Direct Spallation and Evaporation Reactions

Another method to incinerate Cs^{137} is the use of (n,xn) ($x>2$) or (p,x'n) ($x\geq1$) reactions with a high energy neutron or proton. (see Figure 5) When the (n,xn) reaction is used, the neutron flux, of the order of 10^{16} n/cm^2 sec is required, because the cross section is in the order of 1 barn. The neutron energy, however, should be above the neutron binding energy of Cs^{137} (7.9 MeV). This magnitude of high flux is not easily obtained. When a high energy proton is used, a much higher energy is required to reduce ionization losses. It had been suggested by Ichimiya[15] to use the direct spallation and the subsequent evaporation reactions for incinerating Cs^{137}. He estimated the number of transmuting Cs^{137} atoms with a 10 GeV proton to be 85 based mainly on a theoretical extrapolation of an analysis for an experiment carried out with rather low energy protons of 500 MeV to 1 GeV.

In order to examine this estimate, we have independently calculated the transmutation number for Cs^{137} by both a high energy proton and neutron. The calculations were performed using the (NMTC) code. The NMTC code was designed for an analysis of reactions in the energy range from 15 MeV to 3.5 GeV, so that the transmutation numbers for Cs^{137} are calculated as a function of incident nucleon energy range from 50 MeV to 3 GeV and the results are shown in Figure 6.

If we can extrapolate the values around 1 GeV to 3 CeV to the energy of 10 GeV, the total number of transmutations due to 10 GeV proton becomes 37 ± 5. This value is about 43% of Ichimiya's evaluation.

According to our calculation, one neutron with 0.6 GeV energy transmutes 3.8 Cs^{137} and one proton with the same energy transmutes 2.5 Cs^{137}. If each evaporated neutron is assumed to have 50 MeV (which is a high estimate), this neutron transmutes 1.1 Cs^{137} isotopes, whereas, the evaporated proton with 50 MeV energy does not transmute Cs^{137} substantially. Thus the total number of transmutations of Cs^{137} due to a 10 GeV proton is calculated as

$$T_{Cs^{137}} = 1+9x3.8+6x2.5+10x1.1=61.2 \qquad (1)$$

where the numbers and the energies of neutrons and protons produced in the spallation reaction are assumed to be the same as Ichimiya's values. Thus the total number of Cs^{137} transmutations in this calculation becomes 72% of Ichimiya's value of 85.

From an energy balance point of view, in order to produce a 10 GeV proton beam, about 60 GeV of thermal energy is required. This calculation is based on a 50% linear accelerator efficiency and a 33% power conversion efficiency from thermal to electrical energy. In order to produce 60 GeV of thermal energy, 300 fission events are required and 18 Cs^{137} are created in these fissions. The value is a substantial part of the transmutation number of Cs^{137} calculated in the above. Therefore, the spallation approach for using transmuting Cs^{137} is not as efficient as using spallation neutrons from a lead or uranium metal target based on (n,γ) reactions alone.

6. Other Considerations

Besides incinerating Cs^{137} and Sr^{90}, the linear accelerator can be used for incinerating transuranium products by using the neutron produced by the spallation reaction or by together with the direct reaction of spallation and evaporation. That is, instead of a uranium target, use the transuranic as a target material we can effectively incinerate the transuranics together with the fission product Cs^{137} and Sr^{90}. The incineration of transuranics by using a linear accelerator is under study to determine, the neutron yield, and the fission product distribution.

As shown in the Table IV, when a deuteron particle beam is used[11,12] instead of a proton, the neutron yield is increased roughly 20% higher than the proton beam. This is due to the fact that the neutron stripped from deuteron does not lose energy by the ionization which occurs in charged particle beams. And the high energy neutron produced by this reaction produces more neutrons as shown in Figure 6. However, it is estimated that the incremental cost of a deuteron accelerator is more than 20% of a proton accelerator. Furthermore, the disadvantage of a deuteron accelerator is the radioactivity produced by the deuteron collision with beam tube in the lower energy accelerating section.

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TABLE I

Effect of Cs_2O_2 Volume Fraction on Neutron Loss in Pb Target Region, Tr, Tn and Tw of ^{137}Cs and ^{90}Sr

System				
Volume fraction of Cs_2O_2 in D_2O [v/o]		10	50	80
Total loading weight	$W(CS_2O_2)$ [Kg]	0.45×10^3	2.24×10^3	3.58×10^3
W	W(SrO) [Kg]	0.47×10^3	0.47×10^3	0.47×10^3
Neutron loss in target region		0.49	0.34	0.24
Transmutation rate	^{137}Cs	$20.5\ \lambda^{137}$	$11.\ \lambda^{137}$	$8.4\ \lambda^{137}$
Tr [$sec.^{-1}$]	^{90}Sr	$24.6\ \lambda^{90}$	$14.8\ \lambda^{90}$	$14.5\ \lambda^{90}$
No. of transmuted nuclei per	^{137}Cs	7.68	20.8	25.0
a proton, Tn [nuclei/proton]	^{90}Sr	15.01	10.1	8.52
Amounts of transmutation per year Tw [Kg/year]	Cs_2O_2 (Cs)	113 (100)	305 (273)	367 (321)
	SrO (Sr)	155 (134)	104 (89)	88 (75.)

(note):

1. Region width; DX (Cs) = DX(Sr) = 50, DY = DZ = 100, in [cm].
2. Volume fraction; 100% Pb, and 10 v/o SrO in D_2O.
3. $\lambda^{137} = 7.33 \times 10^{-10}$, $\lambda^{90} = 7.82 \times 10^{-10}$, in [$sec.^{-1}$].

TABLE II

Effect of Cs_2O_2 + D_2O Region on Tr, Tn and Tw

System				
Cs_2O_2 + D_2O region width [cm]		50	70	30
Axial dimension DY = DZ [cm]		100	100	100
Total loading weight	$W(CS_2O_2)$ [Kg]	0.358×10^4	0.5×10^4	0.215×10^4
W	W(SrO) [Kg]	0.47×10^3	0.47×10^3	0.47×10^3
Transmutation rate	^{137}Cs	$8.4\ \lambda^{137}$	$6.6\ \lambda^{137}$	$10.\ \lambda^{137}$
Tr [$sec.^{-1}$]	^{90}Sr	$14.5\ \lambda^{90}$	$8.4\ \lambda^{90}$	$30.\ \lambda^{90}$
No. of transmuted nuclei per	^{137}Cs	25.0	28.4	17.7
a proton, Tn [nuclei/proton]	^{90}Sr	8.52	5.0	17.3
Amounts of transmutation per year Tw [Kg/year]	Cs_2O_2	367	418	255
	(Cs)	(329)	(373)	(229)
	SrO	88	51.	183
	(Sr)	75.	(43)	(155)

(note):

1. Region width; DX(Sr) = 50 cm.
2. Volume fraction; 100% Pb, and 10 v/o SrO in D_2O.
3. $\lambda^{137} = 7.33 \times 10^{-10}$, $sec.^{-1}$, $\lambda^{90} = 7.82 \times 10^{-10}$ [$sec.^{-1}$]

TABLE III

Effect of SrO Region on Neutron Capture in Pb Target, Tr, Tn and Tw

System				
Sr region width [cm]		10	20	30
Total loading weight	$W(CS_2O_2)$ [Kg]	0.45×10^3	0.45×10^3	0.45×10^3
W	W(SrO) [Kg]	0.52×10^3	1.04×10^3	1.56×10^3
Neuton capture in Pb target		0.17	0.057	0.038
Transmutation rate	^{137}Cs	$9.4\ \lambda^{137}$	$11.\ \lambda^{137}$	$10.4\ \lambda^{137}$
Tr [$sec.^{-1}$]	^{90}Sr	$35.5\ \lambda^{90}$	$20.3\ \lambda^{90}$	$14.3\ \lambda^{90}$
No. of transmuted nuclei per	^{137}Cs	4.4	4.9	4.3
a proton, Tn [nuclei/proton]	^{90}Sr	32.3	36.7	38.9
Amounts of transmutation per year Tw [Kg/year]	Cs_2O_2 (Cs) Sr	62 (56) 283	72 (64) 321	66 (59) 344

(note):

1. Region width; DX(Cs) = 50, DY=DZ=100, in [cm].
2. Volume fraction; 100% Pb, and 10 v/o Sr, 10 v/o Cs_2O_2 in D_2O.
3. $\lambda^{137} = 7.33 \times 10^{-10}$ $sec.^{-1}$ $\lambda^{90} = 7.82 \times 10^{-10}$ $sec.^{-1}$

TABLE IV

Neutron Yield and Neutron Captured by Uranium Assembly

	Our's (*)( )			Barashenkov	
Target	^{238}U	Nat U	$^{238}U(1/2)$ + Na (1/2)	Nat U	Nat U
Beam	P	P	P	P	d
Fission in High Energy**	4.6	4.6	4.3	6.46	7.0
Fission in Low Energy	47.4	65.5	59.7	23.6	28.4
Total Fission	52.0	70.1	64.0	30.0	35.4
Neutron Yield by High E Reaction	61.6	61.6	59.7	41.7	57.0
^{238}U Capture	92.6***	--	--	100	119
^{235}U Capture	0	—	--	1.2	1.4
Total U Capture	92.6	113.0	—	101.2	120.4
Q_{heat} in Target	10.	14.	—	6.25	7.5
Leakage Neutron	19.5***	22.18	—	—	--

(*) The assembly is the Vasilkov's assembly.

(**) The cut off energies of high energy are respectively 15 MeV and 10 MeV in our calculation and Barashenkov's calculation.

(***) The sum of ^{238}U capture and leakage neutron corresponds to neutron yield.

( ) The statistical error is about 10%.

TABLE V

Thermal Neutron Capture Cross Section,
Half-Life and Fission Yield of Sr and Cs

	^{88}Sr	^{89}Sr	^{90}Sr
2200 m/s capture C.S. (barn)	6.028×10^{-3}	0.42	0.9
Half-life	stable	50 day	28.10 year
% yield	3.57	4.79	5.77

	^{133}Cs	^{134}Cs	^{135}Cs	^{136}Cs	^{137}Cs	^{138}Cs
220 m/s capture C.S. (barn)	29.514	144.79	13.512	5.145	0.11	
Half-life	stable	2.16yr	26×10^{6}y	13.0 day	30.10 yr	2.9 min
% yield	6.59		6.41		6.15	

TABLE VI

Thermal Neutron Capture Cross Section
and Half-Life of Ba

	^{134}Ba	^{136}Ba	^{138}Ba
2200 m/s capture C.S (barn)	6.3358	0.41044	0.35006
Half-Life	stable	stable	stable

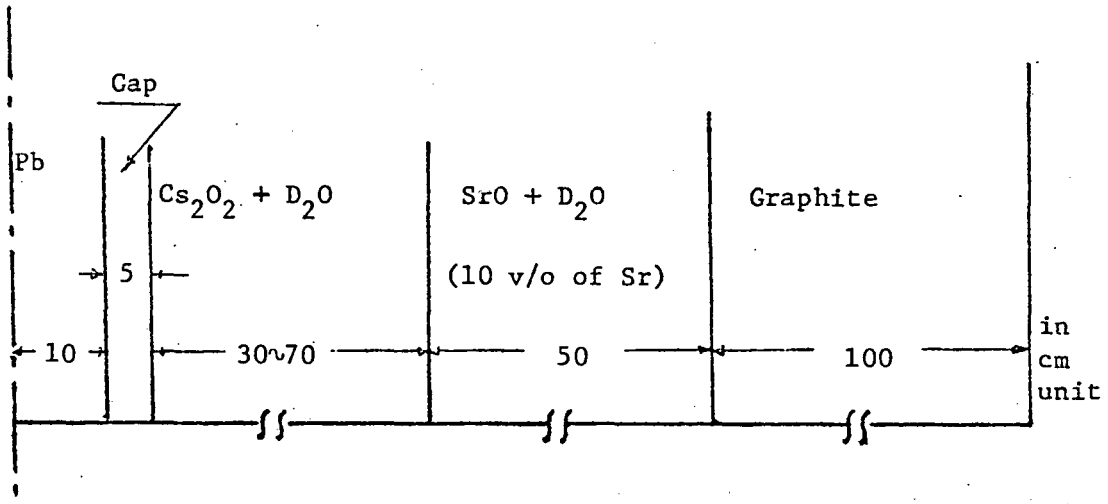


Fig. 1 System Configuration of Table I and II

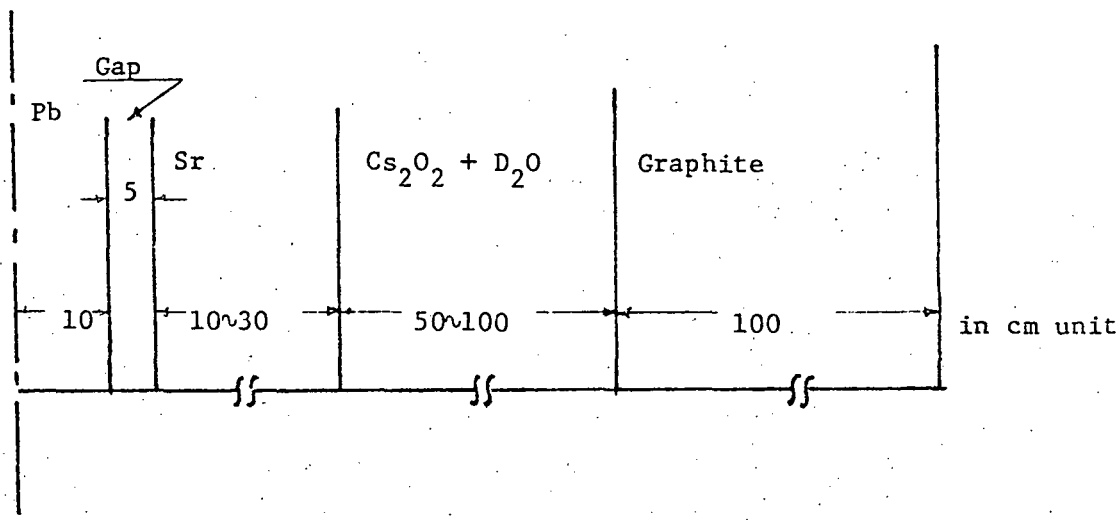


Fig. 2 System Configuration of Table III

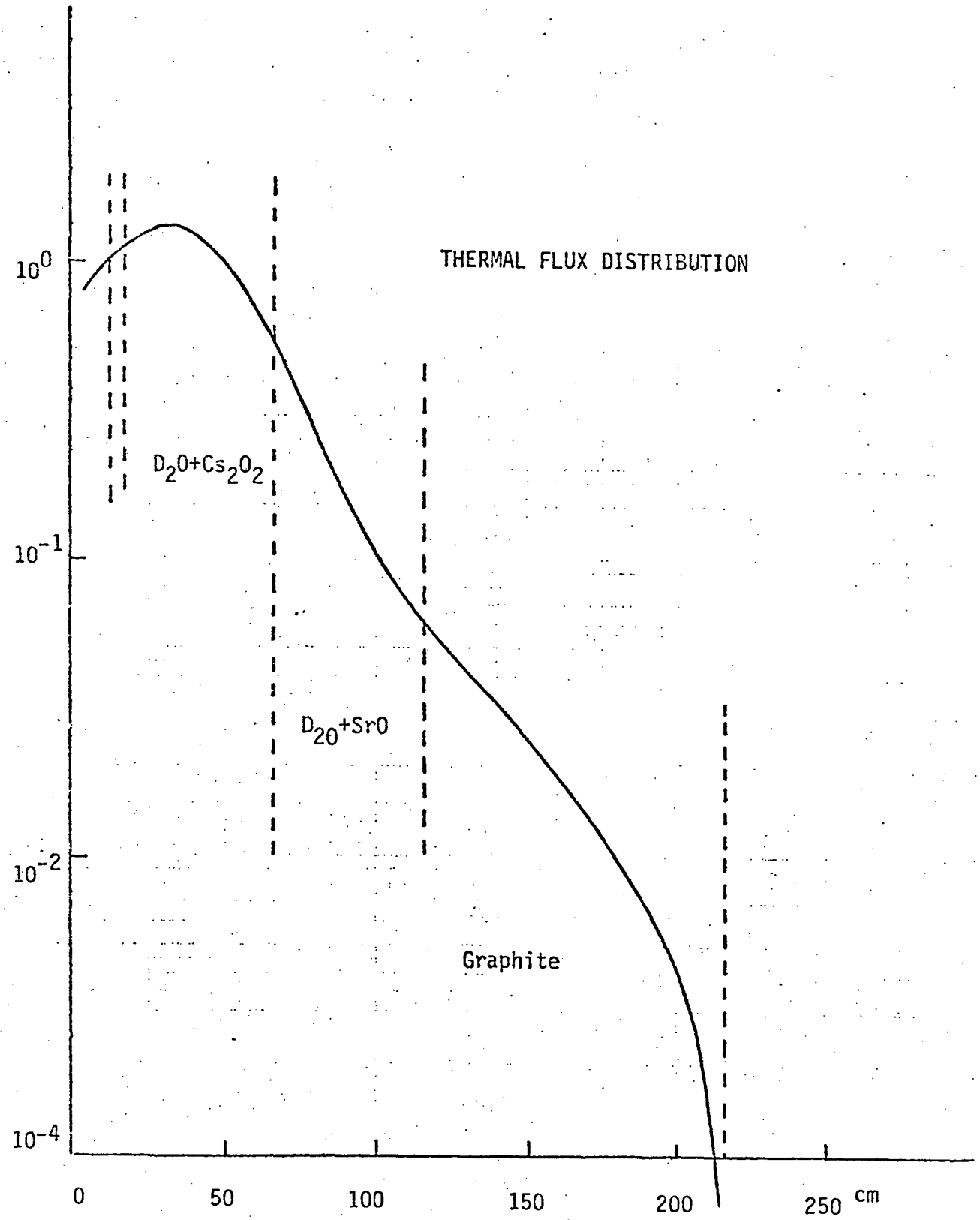
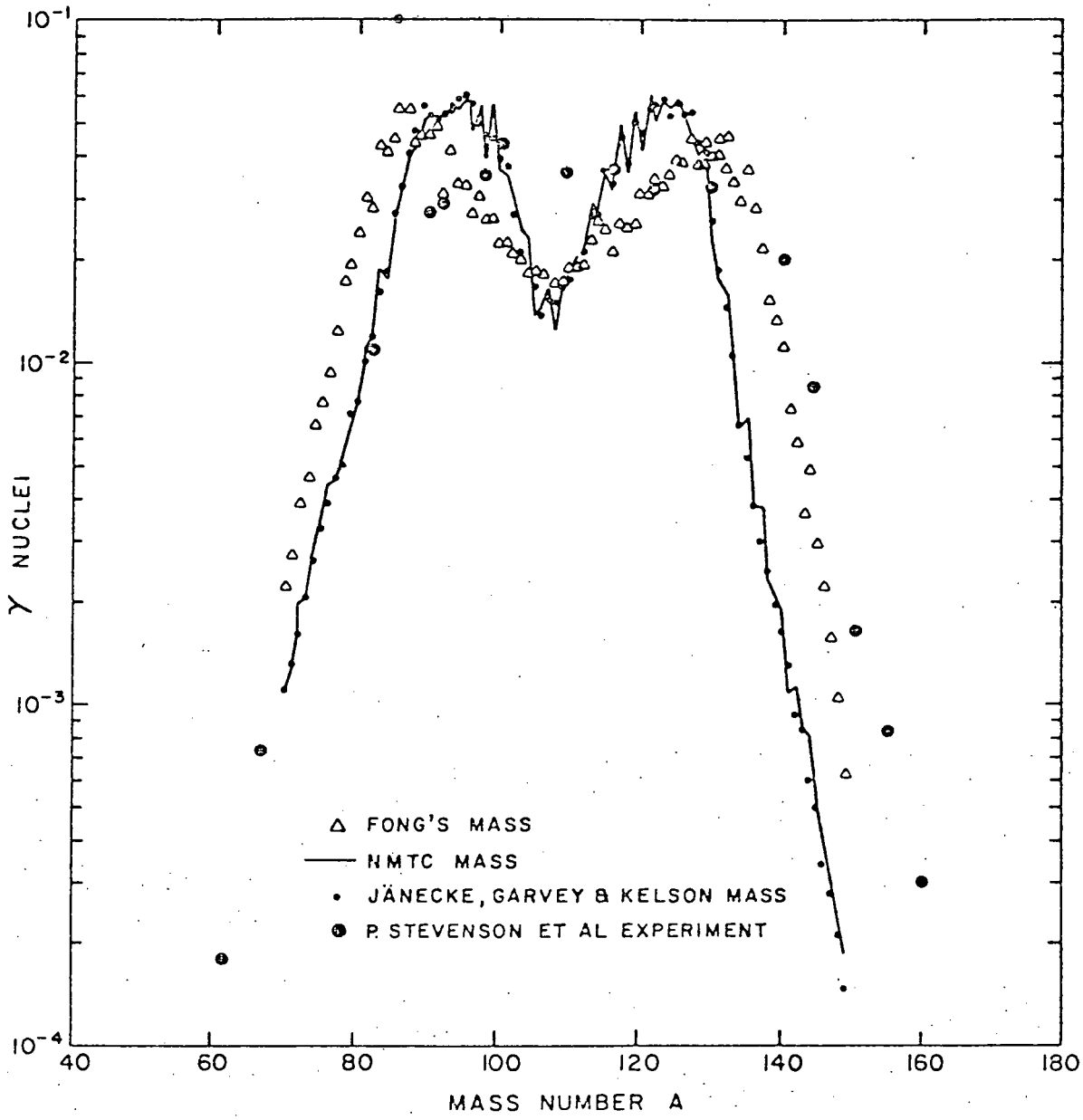


Fig. 3 Thermal Neutron Flux in the System Configuration of Table I. (Width of Cs_2O_2 = 50 cm)



POST EVAPORATION NUCLEI DISTRIBUTION FROM
300 PROTON ON U^{238}

Fig. 4 Post Evaporation Nuclei Distribution From 300 Proton on U^{238}