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Theoretical Yield Limits of In-reactor Medical Isotopes Production

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Abstract

The global shortage of medical isotopes is a common challenge faced by humanity. In-reactor irradiation is the main method of medical isotopes production. Due to the difficulty of precisely regulating the reactor neutron energy spectrum, there is a huge gap between the actual efficiency and the theoretical maximum efficiency of medical isotopes production. We temporarily do not know the theoretical yield limits of various medical isotopes, leading to the impossibility of quantifying this gap and the potential for improving production efficiency. We combined genetic algorithms and burnup algorithms to explore the theoretical yield limits of 20 medical isotopes (^{14}C, ^{32}P, ^{47}Sc, ^{60}Co, ^{64}Cu, ^{67}Cu, ^{89}Sr, ^{90}Y, ^{99}Mo, ^{125}I, ^{131}I, ^{153}Sm, ^{161}Tb, ^{166}Ho, ^{177}Lu, ^{186}Re, ^{188}Re, ^{92}Ir, ^{225}Ac, ^{252}Cf), considering flux levels ranging from 10^{12} to 10^{17} ($cm^{-2}\cdot s^{-1}$), and irradiation times from 5 days to 200 days, providing information such as maximum yield, transmutation rate of nuclides, nuclide abundance, and required irradiation time for 8400 (20×35×12 combinations) scenarios. These data show the limits of nuclides transmutation under the current irradiation conditions, quantify the gap between the current production efficiency and the theoretical maximum production efficiency, and help readers quickly estimate the yield and economy of a reactor for the medical isotopes production.

Keywords: Medical isotopes; Genetic algorithm; In-reactor irradiation; Molybdenum-99; Iodine-131; Lutetium-177; Actinium-225.
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1. Introduction

Medical isotopes, which are indispensable to the nuclear medicine sector, are crucial for the diagnosis and treatment of major diseases such as malignant tumors.[1,2] In recent years, with advancements in medical technology and a greater emphasis on health, the demand for medical isotopes has steadily risen, leading to a global shortage.[3-5] Nature has repeatedly called for attention to the shortage of medical isotopes.[6-8] Achieving efficient production and increasing the yields of medical isotopes has emerged as a pressing concern that can benefit all humanity.

Medical isotopes are produced mainly in reactors and accelerators,[9,10] where reactor-based production of medical isotopes offers the advantages of larger yield, more isotope varieties and lower cost, being the primary production method of medical isotopes.[11] In-reactor medical isotopes production leverages neutron-induced nuclear reactions to achieve nuclide transmutation, such as neutron-induced fission of Uranium-235 (^{235}U) to produce Molybdenum-99 (^{99}Mo) and neutron absorption reactions of Lutetium-176 (^{176}Lu) to produce Lutetium-177 (^{177}Lu), *etc*.[12,13]

Given that the probability of neutron-induced nuclear reactions varies with neutron energy,[14] the neutron spectrum within a reactor significantly impacts the yield of medical isotopes. We have long been invested in exploring the optimal irradiation spectra for medical isotopes production, and have identified the optimal irradiation spectra for various medical isotopes under different irradiation conditions.[15,16] However, due to the difficulties in precisely regulating the neutron spectrum within reactors, the yield limits of various medical isotopes produced within existing reactors remain unknown. This uncertainty further obscures our understanding of the

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disparity between the actual yields and the maximum yields of various medical isotopes produced within reactors.

This study investigates the theoretical yield limits of medical isotopes produced within existing reactors, exploring the limits of nuclide transmutation under the current irradiation conditions. The results provide reference information for production planning and economic analyses for in-reactor medical isotopes.

2. Simulation method

The yields of medical isotopes can be obtained by solving the point burnup equation, which outlines how nuclides transform over time when the target is irradiated in a reactor.[17] The time-dependent point burnup equation for each nuclide is written as Eq. (1):

$$\frac{dn_i}{dt} = \sum_{i \neq j} b_{j,i}^{\text{eff}} \lambda_j^{\text{eff}} n_j - \lambda_i^{\text{eff}} n_i \tag{1}$$

where n_i denotes the density of the i^{th} nuclide, λ_i^{eff} is the effective decay constant of the i^{th} nuclide, and $b_{i,j}^{\text{eff}}$ is the branching ratio for the transmuting the i^{th} nuclide to the j^{th} nuclide. Both λ_i^{eff} and $b_{i,j}^{\text{eff}}$ can be calculated from the following formula,

$$\begin{cases} \lambda_i^{\text{eff}} = \lambda_i + \phi \sum_j \sigma_{i,j} \\ b_{i,j}^{\text{eff}} = (b_{i,j}\lambda_i + \sigma_{i,j}\phi) / \lambda_i^{\text{eff}} \end{cases} \tag{2}$$

where λ_i is the decay constant of the i^{th} nuclide, ϕ stands for the neutron flux, and $\sigma_{i,j}$ is the one-group cross-sections where the i^{th} nuclide's reaction generates the j^{th} nuclide.

As shown in Eq. (2), the calculation of one-group cross-sections, which are integrated based on the neutron spectrum, is essential.[18] This underscores the significant influence that the neutron spectrum within the reactor exerts on the yield of medical isotopes. The yield of medical isotopes reaches its maximum when the optimal irradiation spectrum is employed.

We use genetic algorithms to search for the optimal irradiation spectrum.[19] The individuals of the genetic algorithm represent distinct neutron spectra, with the entire energy range being partitioned into 238 energy bins. Different neutron spectra are obtained by adjusting the proportions of neutron flux across these 238 energy bins. The fitness function of the genetic algorithm is defined by the yield of medical isotopes, as determined through the point burnup calculations. The evolutionary process comprises 200 generations, each featuring a population size of 200 individuals. The selection rate is 50%, meaning that the top 100 individuals with the highest fitness in each generation are carried forward to the next generation. Additionally, the mutation rate of the genetic algorithm is 40%, and the multi-point crossover rate is also 40%.

The genetic algorithm identifies the optimal irradiation spectrum through a systematic process that involves constructing, evaluating, and screening a large number of neutron spectra. During the population evolution process of the genetic algorithm, the one-group cross-sections corresponding to a neutron spectrum necessary for the burnup calculation are calculated by Eq. (3)

(3)

where the subscript "i" represents an energy bin, subscript "r" represents a reaction type, ϕ represents the percentage of neutron flux, and σ represents the grouped cross-section.

Apart from the theoretical maximum yield of medical isotopes (marked as **Y**, representing the number of nuclides per unit volume, in units of at/b·cm), the irradiation time required to achieve the maximum yield (marked as **D**, with unit of days) is also provided, as well as the nuclides transmutation rate corresponding to the maximum yield (marked as **C**), which is calculated by the following formula (Eq. (4)) for nuclei transmutation from isotope#1 to isotope#2,

$$\mathrm{C} = N_2 / N_1 \tag{4}$$

where N_1 is nuclides number per unit volume of isotope#1, N_2 is nuclides number per unit volume of isotope#2.

The nuclide abundance of target medical isotope corresponding to the maximum yield (marked as **A**, with unit of "%") is calculated using the following Eq. (5)

$$\mathrm{A} = N_m / \sum_i N_i \tag{5}$$

where N_m is the nuclides density of the target medical isotope, and N_i is the nuclides density of the i-th isotope of the target medical isotope.

The duration of irradiation and flux levels significantly impact the yield of medical isotopes. Research reactors typically operate with neutron flux levels ranging from 10^{12} to 10^{16} ($\text{cm}^{-2}\cdot\text{s}^{-1}$), with a criticality time being fewer than 200 days. To explore the theoretical yield limits of medical isotopes produced within existing reactors, we examined 12 irradiation times of 5 days, 10 days, 20 days, 40 days, 60 days, 80 days, 100 days, 120 days, 140 days, 160 days, 180 days, 200 days. Additionally, we considered 35 flux levels ($\text{cm}^{-2}\cdot\text{s}^{-1}$) of 1×10^{12}, 5×10^{12}, 1×10^{13}, 2×10^{13}, 3×10^{13}, 4×10^{13}, 5×10^{13}, 6×10^{13}, 7×10^{13}, 8×10^{13}, 9×10^{13}, 1×10^{14}, 2×10^{14}, 3×10^{14}, 4×10^{14}, 5×10^{14}, 6×10^{14}, 7×10^{14}, 8×10^{14}, 9×10^{14}, 1×10^{15}, 2×10^{15}, 3×10^{15}, 4×10^{15}, 5×10^{15}, 6×10^{15}, 7×10^{15}, 8×10^{15},

Table 1: Nuclide components of the target for producing ^{14}C.

Isotopes	Number density (at/b-cm)
^{27}Al	4.7759×10^{22}
^{14}N	4.7543×10^{22}
^{15}N	1.7373×10^{20}
^{12}C	1.6308×10^{19}

Table 2: Theoretical yield limits of ^{14}C under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×1012	(1.51×10-6, 3.18×10-5, 99.99, 200)	8×1014	(1.10×10-3, 2.32×10-2, 100.00, 200)
5×1012	(7.56×10-6, 1.59×10-4, 99.98, 200)	9×1014	(1.23×10-3, 2.59×10-2, 100.00, 200)
1×1013	(1.51×10-5, 3.18×10-4, 99.99, 200)	1×1015	(1.49×10-3, 3.13×10-2, 100.00, 200)
2×1013	(3.02×10-5, 6.36×10-4, 99.97, 200)	2×1015	(3.30×10-3, 6.95×10-2, 100.00, 180)
3×1013	(4.53×10-5, 9.53×10-4, 99.97, 200)	3×1015	(4.42×10-3, 9.29×10-2, 100.00, 200)
4×1013	(6.04×10-5, 1.27×10-3, 99.97, 200)	4×1015	(5.90×10-3, 1.24×10-1, 99.99, 200)
5×1013	(7.55×10-5, 1.59×10-3, 99.97, 200)	5×1015	(1.03×10-2, 2.16×10-1, 100.00, 180)
6×1013	(9.06×10-5, 1.91×10-3, 99.97, 200)	6×1015	(7.71×10-3, 1.62×10-1, 100.00, 200)
7×1013	(1.06×10-4, 2.22×10-3, 99.97, 200)	7×1015	(8.37×10-3, 1.76×10-1, 100.00, 180)
8×1013	(1.21×10-4, 2.54×10-3, 99.97, 200)	8×1015	(1.07×10-2, 2.25×10-1, 99.99, 200)
9×1013	(1.36×10-4, 2.86×10-3, 99.97, 200)	9×1015	(1.20×10-2, 2.52×10-1, 99.99, 180)
1×1014	(1.51×10-4, 3.17×10-3, 99.97, 200)	1×1016	(1.20×10-2, 2.53×10-1, 100.00, 200)
2×1014	(2.91×10-4, 6.11×10-3, 99.97, 200)	2×1016	(2.74×10-2, 5.76×10-1, 100.00, 160)
3×1014	(3.98×10-4, 8.36×10-3, 100.00, 200)	3×1016	(2.83×10-2, 5.95×10-1, 99.99, 180)
4×1014	(5.56×10-4, 1.17×10-2, 100.00, 200)	4×1016	(3.66×10-2, 7.71×10-1, 100.00, 180)
5×1014	(6.88×10-4, 1.45×10-2, 100.00, 200)	5×1016	(3.55×10-2, 7.47×10-1, 100.00, 200)
6×1014	(8.16×10-4, 1.72×10-2, 100.00, 200)	1×1017	(4.39×10-2, 9.23×10-1, 100.00, 200)
7×1014	(9.63×10-4, 2.03×10-2, 100.00, 200)		

9×10^{15}, 1×10^{16}, 2×10^{16}, 3×10^{16}, 4×10^{16}, 5×10^{16}, 1×10^{17}. To provide as much data as possible, we have calculated the theoretical yield limits for 20 medical isotopes of ^{14}C, ^{32}P, ^{47}Sc, ^{60}Co, ^{64}Cu, ^{67}Cu, ^{89}Sr, ^{90}Y, ^{99}Mo, ^{125}I, ^{131}I, ^{153}Sm, ^{161}Tb, ^{166}Ho, ^{177}Lu, ^{186}Re, ^{188}Re, ^{92}Ir, ^{225}Ac, ^{252}Cf. Therefore, we have determined the theoretical yield limits for 8400 irradiation conditions, derived from the combinations of 12 irradiation times, 35 neutron flux levels, and 20 medical isotopes (12×35×20).

3. Theoretical yield limits

3.1 Carbon-14 (^{14}C)

^{14}C undergoes β^- decay with a half-life of 5730 years and an average ray energy of 49.47 keV. ^{14}C is produced by in-reactor irradiation of aluminum nitride (AlN) through nuclei transmutation of $^{14}_{7}N(n,p)^{14}_{6}C$. The nuclide components of the target are shown in Table 1. The theoretical yield limits of ^{14}C are given in Table 2.

3.2 Phosphorus-32 (^{32}P)

^{32}P undergoes β^- decay with a half-life of 14.3 days and an average ray energy of 0.69 MeV. ^{32}P is produced by in-reactor irradiation of natural phosphorus through nuclei transmutation of $^{31}_{15}P(n,\gamma)^{32}_{15}P$. The nuclide components of the target are shown in Table 3. The theoretical yield limits of ^{32}P are given in Table 4.

Table 3: Nuclide components of the target for producing ${}^{32}P$.

Isotopes	Number density (at/b-cm)
${}^{31}P$	4.5494×10^{22}
${}^{16}O$	4.4050×10^{17}
${}^{28}Si$	2.3225×10^{17}
${}^{29}Si$	1.1392×10^{16}
${}^{30}Si$	7.2683×10^{15}

Table 4: Theoretical yield limits of ${}^{32}P$ under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	(1.40×10^{-8}, 3.08×10^{-7}, 0.00003, 200)	8×10^{14}	(1.13×10^{-5}, 2.48×10^{-4}, 0.02491, 140)
5×10^{12}	(6.99×10^{-8}, 1.54×10^{-6}, 0.00015, 200)	9×10^{14}	(1.32×10^{-5}, 2.90×10^{-4}, 0.02900, 200)
1×10^{13}	(1.40×10^{-7}, 3.08×10^{-6}, 0.00031, 200)	1×10^{15}	(1.49×10^{-5}, 3.28×10^{-4}, 0.03283, 200)
2×10^{13}	(2.79×10^{-7}, 6.13×10^{-6}, 0.00062, 200)	2×10^{15}	(2.99×10^{-5}, 6.57×10^{-4}, 0.06609, 160)
3×10^{13}	(4.19×10^{-7}, 9.21×10^{-6}, 0.00093, 200)	3×10^{15}	(4.02×10^{-5}, 8.84×10^{-4}, 0.08881, 160)
4×10^{13}	(5.59×10^{-7}, 1.23×10^{-5}, 0.00124, 200)	4×10^{15}	(6.25×10^{-5}, 1.37×10^{-3}, 0.13874 140)
5×10^{13}	(8.46×10^{-7}, 1.86×10^{-5}, 0.00186, 200)	5×10^{15}	(8.66×10^{-5}, 1.90×10^{-3}, 0.19406, 200)
6×10^{13}	(1.01×10^{-6}, 2.22×10^{-5}, 0.00223, 200)	6×10^{15}	(8.52×10^{-5}, 1.87×10^{-3}, 0.18953, 160)
7×10^{13}	(1.18×10^{-6}, 2.59×10^{-5}, 0.00260, 200)	7×10^{15}	(1.13×10^{-4}, 2.48×10^{-3}, 0.25306, 200)
8×10^{13}	(1.35×10^{-6}, 2.97×10^{-5}, 0.00297, 200)	8×10^{15}	(1.29×10^{-4}, 2.84×10^{-3}, 0.28917, 180)
9×10^{13}	(1.52×10^{-6}, 3.34×10^{-5}, 0.00335, 200)	9×10^{15}	(2.57×10^{-4}, 5.65×10^{-3}, 0.57524, 80)
1×10^{14}	(1.69×10^{-6}, 3.71×10^{-5}, 0.00372, 180)	1×10^{16}	(1.39×10^{-4}, 3.06×10^{-3}, 0.31415, 180)
2×10^{14}	(2.99×10^{-6}, 6.57×10^{-5}, 0.00658, 140)	2×10^{16}	(2.79×10^{-4}, 6.13×10^{-3}, 0.65039, 100)
3×10^{14}	(3.90×10^{-6}, 8.57×10^{-5}, 0.00857, 100)	3×10^{16}	(4.22×10^{-4}, 9.28×10^{-3}, 1.01419, 200)
4×10^{14}	(5.36×10^{-6}, 1.18×10^{-4}, 0.01181, 140)	4×10^{16}	(5.80×10^{-4}, 1.27×10^{-2}, 1.31191, 60)
5×10^{14}	(7.42×10^{-6}, 1.63×10^{-4}, 0.01631, 200)	5×10^{16}	(6.99×10^{-4}, 1.54×10^{-2}, 1.63818, 80)
6×10^{14}	(8.20×10^{-6}, 1.80×10^{-4}, 0.01803, 160)	1×10^{17}	(2.09×10^{-3}, 4.59×10^{-2}, 6.96824, 140)
7×10^{14}	(9.56×10^{-6}, 2.10×10^{-4}, 0.02102, 140)		

3.3 Scandium-47 (${}^{47}Sc$)

${}^{47}Sc$ undergoes β^- and λ decays with a half-life of 3.35 days and average ray energies of 0.49 MeV (β^-) and 0.16 MeV (λ). ${}^{47}Sc$ is produced by in-reactor irradiation of titanium dioxide (TiO_2) through nuclei transmutation of ${}^{47}_{22}Ti(n,p){}^{47}_{21}Sc$. The nuclide components of the target are shown in Table 5. The theoretical yield limits of ${}^{47}Sc$ under different neutron fluxes are given in Table 6.

3.4 Cobalt-60 (${}^{60}Co$)

${}^{60}Co$ undergoes λ decay with a half-life of 5.27 years, and the λ rays have energies of 1.332 MeV and 1.173 MeV. ${}^{60}Co$ is produced by in-reactor irradiation of cobalt metal through nuclei transmutation of ${}^{59}_{27}Co(n,\gamma){}^{60}_{27}Co$. The nuclide components of the target are shown in Table 7. The theoretical yield limits of ${}^{60}Co$ under different neutron fluxes are given in Table 8.

Table 5: Nuclide components of the target for producing ^{47}Sc.

Isotopes	Number density (at/b-cm)	isotopes	Number density (at/b-cm)
^{16}O	1.2951×10^{22}	^{48}Ti	9.0267×10^{20}
^{46}Ti	6.6653×10^{19}	^{49}Ti	3.8087×10^{19}
^{47}Ti	1.8002×10^{22}	^{50}Ti	3.4279×10^{19}

Table 6: Theoretical yield limits of ^{47}Sc under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	(9.62×10^{-10}, 5.34×10^{-8}, 97.54, 180)	8×10^{14}	6.54×10^{-7}, 3.63×10^{-5}, 97.41, 100)
5×10^{12}	(5.22×10^{-9}, 2.90×10^{-7}, 97.29, 180)	9×10^{14}	7.41×10^{-7}, 4.12×10^{-5}, 97.31, 80)
1×10^{13}	(1.06×10^{-8}, 5.88×10^{-7}, 97.29, 80)	1×10^{15}	8.97×10^{-7}, 4.98×10^{-5}, 97.57, 200)
2×10^{13}	(1.79×10^{-8}, 9.92×10^{-7}, 97.43, 80)	2×10^{15}	1.65×10^{-6}, 9.19×10^{-5}, 98.33, 80)
3×10^{13}	(2.81×10^{-8}, 1.56×10^{-6}, 97.35, 140)	3×10^{15}	2.44×10^{-6}, 1.36×10^{-4}, 98.01, 20)
4×10^{13}	(3.42×10^{-8}, 1.90×10^{-6}, 97.92, 10)	4×10^{15}	3.37×10^{-6}, 1.87×10^{-4}, 97.41, 120)
5×10^{13}	(4.95×10^{-8}, 2.75×10^{-6}, 97.94 200)	5×10^{15}	4.21×10^{-6}, 2.34×10^{-4}, 97.48, 100)
6×10^{13}	(5.87×10^{-8}, 3.26×10^{-6}, 97.40, 120)	6×10^{15}	4.65×10^{-6}, 2.58×10^{-4}, 97.34, 40)
7×10^{13}	(5.53×10^{-8}, 3.07×10^{-6}, 97.39, 180)	7×10^{15}	5.64×10^{-6}, 3.13×10^{-4}, 97.37, 160)
8×10^{13}	(7.60×10^{-8}, 4.22×10^{-6}, 97.69, 100)	8×10^{15}	6.42×10^{-6}, 3.57×10^{-4}, 97.47, 40)
9×10^{13}	(7.44×10^{-8}, 4.13×10^{-6}, 97.36, 160)	9×10^{15}	8.13×10^{-6}, 4.52×10^{-4}, 97.02, 120)
1×10^{14}	(9.48×10^{-8}, 5.26×10^{-6}, 97.51, 200)	1×10^{16}	8.16×10^{-6}, 4.53×10^{-4}, 98.16, 80)
2×10^{14}	(2.05×10^{-7}, 1.14×10^{-5}, 97.29, 180)	2×10^{16}	1.71×10^{-5}, 9.48×10^{-4}, 97.09, 80)
3×10^{14}	(2.91×10^{-7}, 1.61×10^{-5}, 97.48, 20)	3×10^{16}	2.39×10^{-5}, 1.33×10^{-3}, 96.65, 60)
4×10^{14}	(3.42×10^{-7}, 1.90×10^{-5}, 97.44, 60)	4×10^{16}	3.13×10^{-5}, 1.74×10^{-3}, 97.36, 100)
5×10^{14}	(4.91×10^{-7}, 2.73×10^{-5}, 97.30, 20)	5×10^{16}	4.18×10^{-5}, 2.32×10^{-3}, 96.57, 20)
6×10^{14}	(5.14×10^{-7}, 2.85×10^{-5}, 97.34, 100)	1×10^{17}	8.20×10^{-5}, 4.56×10^{-3}, 93.74, 20)
7×10^{14}	(6.87×10^{-7}, 3.81×10^{-5}, 97.27, 200)		

Table 7: Nuclide components of the target for producing ^{60}Co.

isotopes	Number density (at/b-cm)
^{59}Co	9.0671×10^{22}
^{58}Ni	2.7753×10^{20}

Table 8: Theoretical yield limits of ^{60}Co under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	$(6.32\times10^{-5}, 6.97\times10^{-4}, 0.15, 200)$	8×10^{14}	$3.79\times10^{-2}, 4.18\times10^{-1}, 69.12, 200$
5×10^{12}	$(3.16\times10^{-4}, 3.48\times10^{-3}, 0.73, 200)$	9×10^{14}	$4.35\times10^{-2}, 4.79\times10^{-1}, 76.05, 200$
1×10^{13}	$(6.30\times10^{-4}, 6.95\times10^{-3}, 1.46, 200)$	1×10^{15}	$4.39\times10^{-2}, 4.84\times10^{-1}, 76.15, 200$
2×10^{13}	$(1.08\times10^{-3}, 1.20\times10^{-2}, 2.47, 200)$	2×10^{15}	$6.43\times10^{-2}, 7.09\times10^{-1}, 94.04, 200$
3×10^{13}	$(1.62\times10^{-3}, 1.79\times10^{-2}, 3.69, 200)$	3×10^{15}	$7.58\times10^{-2}, 8.36\times10^{-1}, 98.87, 200$
4×10^{13}	$(2.15\times10^{-3}, 2.38\times10^{-2}, 4.89, 200)$	4×10^{15}	$8.10\times10^{-2}, 8.93\times10^{-1}, 99.54, 80$
5×10^{13}	$(2.68\times10^{-3}, 2.96\times10^{-2}, 6.07, 200)$	5×10^{15}	$8.27\times10^{-2}, 9.12\times10^{-1}, 99.91, 160$
6×10^{13}	$(3.21\times10^{-3}, 3.54\times10^{-2}, 7.26, 200)$	6×10^{15}	$8.24\times10^{-2}, 9.09\times10^{-1}, 99.96, 180$
7×10^{13}	$(3.74\times10^{-3}, 4.12\times10^{-2}, 8.42, 200)$	7×10^{15}	$8.54\times10^{-2}, 9.41\times10^{-1}, 100.00, 100$
8×10^{13}	$(4.33\times10^{-3}, 4.77\times10^{-2}, 9.70, 200)$	8×10^{15}	$8.39\times10^{-2}, 9.25\times10^{-1}, 99.99, 160$
9×10^{13}	$(4.85\times10^{-3}, 5.35\times10^{-2}, 10.85, 200)$	9×10^{15}	$8.47\times10^{-2}, 9.34\times10^{-1}, 100.00, 140$
1×10^{14}	$(5.81\times10^{-3}, 6.41\times10^{-2}, 13.03, 200)$	1×10^{16}	$8.46\times10^{-2}, 9.33\times10^{-1}, 100.00, 80$
2×10^{14}	$(1.04\times10^{-2}, 1.15\times10^{-1}, 22.52, 200)$	2×10^{16}	$8.59\times10^{-2}, 9.47\times10^{-1}, 99.99, 60$
3×10^{14}	$(1.53\times10^{-2}, 1.68\times10^{-1}, 32.16, 200)$	3×10^{16}	$8.62\times10^{-2}, 9.51\times10^{-1}, 99.99, 40$
4×10^{14}	$(2.01\times10^{-2}, 2.22\times10^{-1}, 41.26, 200)$	4×10^{16}	$8.67\times10^{-2}, 9.57\times10^{-1}, 99.99, 40$
5×10^{14}	$(2.39\times10^{-2}, 2.64\times10^{-1}, 47.75, 200)$	5×10^{16}	$8.71\times10^{-2}, 9.60\times10^{-1}, 99.99, 20$
6×10^{14}	$(3.63\times10^{-2}, 4.00\times10^{-1}, 68.19, 140)$	1×10^{17}	$8.67\times10^{-2}, 9.56\times10^{-1}, 99.98, 20$
7×10^{14}	$(3.64\times10^{-2}, 4.02\times10^{-1}, 68.28, 120)$		

Table 9: Nuclide components of the target for producing ^{64}Cu.

isotopes	Number density (at/b-cm)
^{63}Cu	4.8833×10^{22}
^{16}O	4.8833×10^{22}

3.5 Copper-64 (^{64}Cu)

^{64}Cu undergoes β^- and β^+ decays with a half-life of 12.7 hours and average ray energies of 0.45 MeV (β^-) and 0.66 MeV (β^+). ^{64}Cu is produced by in-reactor irradiation of copper oxide (CuO) through nuclei transmutation of ${}^{63}_{29}Cu(n,\gamma){}^{64}_{29}Cu$. The nuclide components of the target are shown in Table 9. The theoretical yield limits of ^{64}Cu under different neutron fluxes are given in Table 10.

3.6 Copper-67 (^{67}Cu)

^{67}Cu undergoes β^- and λ decays with a half-life of 61.83 hours and average ray energies of 0.45 MeV (β^-) and 0.11 MeV (λ). ^{67}Cu is produced by in-reactor irradiation of zinc metal through nuclei transmutation of ${}^{67}_{30}Zn(n,p\gamma){}^{67}_{29}Cu$. The nuclide components of the target are shown in Table 11. The theoretical yield limits of ^{67}Cu under different neutron fluxes are given in Table 12.

Table 10: Theoretical yield limits of ^{64}Cu under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	$(1.90\times10^{-8}, 3.90\times10^{-7}, 0.00004, 160)$	8×10^{14}	$(1.61\times10^{-5}, 3.31\times10^{-4}, 0.03309, 40)$
5×10^{12}	$(9.52\times10^{-8}, 1.95\times10^{-6}, 0.00019, 160)$	9×10^{14}	$(1.88\times10^{-5}, 3.86\times10^{-4}, 0.04543, 5)$
1×10^{13}	$(1.90\times10^{-7}, 3.89\times10^{-6}, 0.00039, 160)$	1×10^{15}	$(2.59\times10^{-5}, 5.30\times10^{-4}, 0.05741, 40)$
2×10^{13}	$(3.91\times10^{-7}, 8.01\times10^{-6}, 0.00080, 80)$	2×10^{15}	$(5.57\times10^{-5}, 1.14\times10^{-3}, 0.13321, 5)$
3×10^{13}	$(7.36\times10^{-7}, 1.51\times10^{-5}, 0.00150, 120)$	3×10^{15}	$(4.93\times10^{-5}, 1.01\times10^{-3}, 0.16289, 140)$
4×10^{13}	$(7.61\times10^{-7}, 1.56\times10^{-5}, 0.00154, 120)$	4×10^{15}	$(7.88\times10^{-5}, 1.61\times10^{-3}, 0.20210, 5)$
5×10^{13}	$(8.62\times10^{-7}, 1.77\times10^{-5}, 0.00177, 60)$	5×10^{15}	$(6.47\times10^{-5}, 1.33\times10^{-3}, 0.17319, 40)$
6×10^{13}	$(9.31\times10^{-7}, 1.91\times10^{-5}, 0.00191, 5)$	6×10^{15}	$(7.80\times10^{-5}, 1.60\times10^{-3}, 0.23456, 10)$
7×10^{13}	$(1.32\times10^{-6}, 2.70\times10^{-5}, 0.00273, 160)$	7×10^{15}	$(8.35\times10^{-5}, 1.71\times10^{-3}, 0.32094, 20)$
8×10^{13}	$(1.46\times10^{-6}, 2.98\times10^{-5}, 0.00302, 20)$	8×10^{15}	$(9.32\times10^{-5}, 1.91\times10^{-3}, 0.33489, 5)$
9×10^{13}	$(1.44\times10^{-6}, 2.95\times10^{-5}, 0.00297, 60)$	9×10^{15}	$(1.03\times10^{-4}, 2.10\times10^{-3}, 0.50697, 60)$
1×10^{14}	$(1.62\times10^{-6}, 3.31\times10^{-5}, 0.00334, 40)$	1×10^{16}	$(1.11\times10^{-4}, 2.28\times10^{-3}, 0.31567, 5)$
2×10^{14}	$(3.73\times10^{-6}, 7.64\times10^{-5}, 0.00747, 200)$	2×10^{16}	$(1.86\times10^{-4}, 3.81\times10^{-3}, 0.65863, 10)$
3×10^{14}	$(6.91\times10^{-6}, 1.42\times10^{-4}, 0.01443, 10)$	3×10^{16}	$(2.04\times10^{-4}, 4.18\times10^{-3}, 0.90227, 10)$
4×10^{14}	$(7.73\times10^{-6}, 1.58\times10^{-4}, 0.01653, 120)$	4×10^{16}	$(2.24\times10^{-4}, 4.58\times10^{-3}, 1.27252, 10)$
5×10^{14}	$(7.79\times10^{-6}, 1.60\times10^{-4}, 0.01643, 60)$	5×10^{16}	$(2.62\times10^{-4}, 5.37\times10^{-3}, 1.77234, 5)$
6×10^{14}	$(1.15\times10^{-5}, 2.36\times10^{-4}, 0.02475, 60)$	1×10^{17}	$(2.89\times10^{-4}, 5.91\times10^{-3}, 1.43826, 5)$
7×10^{14}	$(1.77\times10^{-5}, 3.63\times10^{-4}, 0.03924, 60)$		

Table 11: Nuclide components of the target for producing ^{67}Cu.

Isotopes	Number density (at/b-cm)
^{67}Zn	6.0390×10^{22}
^{64}Zn	2.0581×10^{21}
^{66}Zn	1.1479×10^{21}
^{68}Zn	7.4696×10^{19}

Table 12: Theoretical yield limits of ^{67}Cu under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	(9.22×10^{-10}, 1.53×10^{-8}, 73.41, 80)	8×10^{14}	(7.34×10^{-7}, 1.22×10^{-5}, 73.37, 60)
5×10^{12}	(4.63×10^{-9}, 7.67×10^{-8}, 73.36, 140)	9×10^{14}	(8.24×10^{-7}, 1.36×10^{-5}, 73.42, 20)
1×10^{13}	(9.25×10^{-9}, 1.53×10^{-7}, 73.46, 180)	1×10^{15}	(9.18×10^{-7}, 1.52×10^{-5}, 73.66, 60)
2×10^{13}	(1.85×10^{-8}, 3.06×10^{-7}, 73.37, 120)	2×10^{15}	(1.83×10^{-6}, 3.02×10^{-5}, 73.26, 20)
3×10^{13}	(2.77×10^{-8}, 4.58×10^{-7}, 73.51, 100)	3×10^{15}	(2.74×10^{-6}, 4.54×10^{-5}, 73.44, 20)
4×10^{13}	(3.68×10^{-8}, 6.10×10^{-7}, 73.36, 100)	4×10^{15}	(3.66×10^{-6}, 6.06×10^{-5}, 73.38, 40)
5×10^{13}	(4.63×10^{-8}, 7.66×10^{-7}, 73.58, 100)	5×10^{15}	(4.54×10^{-6}, 7.52×10^{-5}, 73.98, 20)
6×10^{13}	(5.53×10^{-8}, 9.16×10^{-7}, 73.82, 100)	6×10^{15}	(5.43×10^{-6}, 8.99×10^{-5}, 72.99, 20)
7×10^{13}	(6.46×10^{-8}, 1.07×10^{-6}, 73.35, 160)	7×10^{15}	(6.33×10^{-6}, 1.05×10^{-4}, 73.40, 20)
8×10^{13}	(7.39×10^{-8}, 1.22×10^{-6}, 73.36, 120)	8×10^{15}	(7.22×10^{-6}, 1.20×10^{-4}, 73.51, 20)
9×10^{13}	(8.31×10^{-8}, 1.38×10^{-6}, 73.51, 140)	9×10^{15}	(8.10×10^{-6}, 1.34×10^{-4}, 73.26, 20)
1×10^{14}	(9.22×10^{-8}, 1.53×10^{-6}, 73.65, 20)	1×10^{16}	(8.98×10^{-6}, 1.49×10^{-4}, 73.12, 20)
2×10^{14}	(1.84×10^{-7}, 3.05×10^{-6}, 73.66, 20)	2×10^{16}	(1.76×10^{-5}, 2.91×10^{-4}, 72.97, 20)
3×10^{14}	(2.76×10^{-7}, 4.57×10^{-6}, 73.47, 160)	3×10^{16}	(2.59×10^{-5}, 4.28×10^{-4}, 73.03, 20)
4×10^{14}	(3.67×10^{-7}, 6.08×10^{-6}, 74.19, 40)	4×10^{16}	(3.38×10^{-5}, 5.59×10^{-4}, 72.73, 20)
5×10^{14}	(4.59×10^{-7}, 7.60×10^{-6}, 73.43, 60)	5×10^{16}	(4.14×10^{-5}, 6.86×10^{-4}, 72.69, 20)
6×10^{14}	(5.51×10^{-7}, 9.12×10^{-6}, 73.78, 40)	1×10^{17}	(7.76×10^{-5}, 1.29×10^{-3}, 71.92, 10)
7×10^{14}	(6.42×10^{-7}, 1.06×10^{-5}, 73.26, 40)		

Table 13: Nuclide components of the target for producing ^{89}Sr.

isotopes	Number density (at/b-cm)	isotopes	Number density (at/b-cm)
^{88}Sr	1.6213×10^{22}	^{16}O	4.8836×10^{22}
^{84}Sr	1.7010×10^{17}	^{27}Al	2.6728×10^{17}
^{86}Sr	9.6199×10^{18}	^{56}Fe	2.1489×10^{18}
^{87}Sr	6.7502×10^{18}	^{207}Pb	1.1614×10^{16}

3.7 Strontium-89 (^{89}Sr)

^{89}Sr undergoes β^- decay with a half-life of 50.6 days and an average ray energy of 0.587 MeV. ^{89}Sr is produced by in-reactor irradiation of strontium carbonate through nuclei transmutation of $^{88}_{38}Sr(n,\gamma)^{89}_{38}Sr$. The nuclide components of the target are shown in Table 13. The theoretical yield limits of ^{89}Sr under different neutron fluxes are given in Table 14.

3.8 Yttrium-90 (^{90}Y)

^{90}Y undergoes β^- decay with a half-life of 64.0 hours and a maximum ray energy of 2.28 MeV. ^{90}Y is produced by in-reactor irradiation of a mixture of Y_2O_3, SiO_2 and Al_2O_3 through nuclei transmutation of $^{89}_{39}Y(n,\gamma)^{90}_{39}Y$. The nuclide components of the target are shown in Table 15. The theoretical yield limits of ^{90}Y under different neutron fluxes are given in Table 16.

Table 14: Theoretical yield limits of ^{89}Sr under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	$(8.85\times10^{-10}, 5.46\times10^{-8}, 0.00001, 200)$	8×10^{14}	$(1.03\times10^{-6}, 6.35\times10^{-5}, 0.00635, 120)$
5×10^{12}	$(4.42\times10^{-9}, 2.72\times10^{-7}, 0.00003, 200)$	9×10^{14}	$(8.69\times10^{-7}, 5.36\times10^{-5}, 0.00509, 160)$
1×10^{13}	$(8.99\times10^{-9}, 5.54\times10^{-7}, 0.00005, 180)$	1×10^{15}	$(1.20\times10^{-6}, 7.40\times10^{-5}, 0.00736, 160)$
2×10^{13}	$(1.77\times10^{-8}, 1.09\times10^{-6}, 0.00011, 160)$	2×10^{15}	$(1.89\times10^{-6}, 1.17\times10^{-4}, 0.01161, 200)$
3×10^{13}	$(2.69\times10^{-8}, 1.66\times10^{-6}, 0.00017, 200)$	3×10^{15}	$(2.89\times10^{-6}, 1.78\times10^{-4}, 0.01779, 180)$
4×10^{13}	$(3.66\times10^{-8}, 2.26\times10^{-6}, 0.00023, 200)$	4×10^{15}	$(5.51\times10^{-6}, 3.40\times10^{-4}, 0.03410, 180)$
5×10^{13}	$(5.48\times10^{-8}, 3.38\times10^{-6}, 0.00034, 200)$	5×10^{15}	$(4.49\times10^{-6}, 2.77\times10^{-4}, 0.02768, 200)$
6×10^{13}	$(5.71\times10^{-8}, 3.52\times10^{-6}, 0.00035, 160)$	6×10^{15}	$(6.15\times10^{-6}, 3.79\times10^{-4}, 0.03783, 160)$
7×10^{13}	$(7.41\times10^{-8}, 4.57\times10^{-6}, 0.00046, 160)$	7×10^{15}	$(6.06\times10^{-6}, 3.74\times10^{-4}, 0.03729, 160)$
8×10^{13}	$(7.64\times10^{-8}, 4.71\times10^{-6}, 0.00047, 200)$	8×10^{15}	$(9.26\times10^{-6}, 5.71\times10^{-4}, 0.05701, 200)$
9×10^{13}	$(9.92\times10^{-8}, 6.12\times10^{-6}, 0.00062, 200)$	9×10^{15}	$(1.08\times10^{-5}, 6.66\times10^{-4}, 0.06681, 120)$
1×10^{14}	$(1.08\times10^{-7}, 6.66\times10^{-6}, 0.00067, 180)$	1×10^{16}	$(9.74\times10^{-6}, 6.00\times10^{-4}, 0.06007, 180)$
2×10^{14}	$(2.19\times10^{-7}, 1.35\times10^{-5}, 0.00135, 160)$	2×10^{16}	$(1.83\times10^{-5}, 1.13\times10^{-3}, 0.11257, 160)$
3×10^{14}	$(4.94\times10^{-7}, 3.05\times10^{-5}, 0.00304, 200)$	3×10^{16}	$(2.70\times10^{-5}, 1.66\times10^{-3}, 0.16681, 200)$
4×10^{14}	$(6.34\times10^{-7}, 3.91\times10^{-5}, 0.00390, 140)$	4×10^{16}	$(3.98\times10^{-5}, 2.45\times10^{-3}, 0.24639, 200)$
5×10^{14}	$(4.81\times10^{-7}, 2.97\times10^{-5}, 0.00295, 200)$	5×10^{16}	$(4.58\times10^{-5}, 2.82\times10^{-3}, 0.28293, 180)$
6×10^{14}	$(5.61\times10^{-7}, 3.46\times10^{-5}, 0.00344, 200)$	1×10^{17}	$(7.48\times10^{-5}, 4.61\times10^{-3}, 0.46507, 160)$
7×10^{14}	$(7.67\times10^{-7}, 4.73\times10^{-5}, 0.00471, 120)$		

Table 15: Nuclide components of the target for producing ^{90}Y.

isotopes	Number density (at/b-cm)	isotopes	Number density (at/b-cm)
^{89}Y	6.9354×10^{21}	^{30}Si	3.7863×10^{20}
^{28}Si	1.2069×10^{22}	^{27}Al	7.6804×10^{21}
^{29}Si	5.9001×10^{20}	^{16}O	4.7968×10^{22}

Table 16: Theoretical yield limits of ^{90}Y under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	(2.71×10^{-9}, 3.91×10^{-7}, 0.00004, 80)	8×10^{14}	(2.63×10^{-6}, 3.79×10^{-4}, 0.03877, 200)
5×10^{12}	(1.36×10^{-8}, 1.95×10^{-6}, 0.00020, 80)	9×10^{14}	(3.00×10^{-6}, 4.33×10^{-4}, 0.04402, 120)
1×10^{13}	(2.71×10^{-8}, 3.91×10^{-6}, 0.00039, 60)	1×10^{15}	(3.29×10^{-6}, 4.74×10^{-4}, 0.04845, 160)
2×10^{13}	(5.42×10^{-8}, 7.82×10^{-6}, 0.00078, 40)	2×10^{15}	(5.90×10^{-6}, 8.51×10^{-4}, 0.08657, 80)
3×10^{13}	(9.00×10^{-8}, 1.30×10^{-5}, 0.00130, 200)	3×10^{15}	(9.68×10^{-6}, 1.40×10^{-3}, 0.14040, 20)
4×10^{13}	(1.19×10^{-7}, 1.71×10^{-5}, 0.00172, 160)	4×10^{15}	(1.17×10^{-5}, 1.69×10^{-3}, 0.17744, 60)
5×10^{13}	(1.50×10^{-7}, 2.16×10^{-5}, 0.00217, 120)	5×10^{15}	(1.96×10^{-5}, 2.83×10^{-3}, 0.28653, 20)
6×10^{13}	(1.80×10^{-7}, 2.60×10^{-5}, 0.00260, 100)	6×10^{15}	(2.12×10^{-5}, 3.06×10^{-3}, 0.36171, 180)
7×10^{13}	(2.09×10^{-7}, 3.01×10^{-5}, 0.00302, 160)	7×10^{15}	(2.05×10^{-5}, 2.96×10^{-3}, 0.30432, 20)
8×10^{13}	(2.75×10^{-7}, 3.97×10^{-5}, 0.00399, 200)	8×10^{15}	(3.62×10^{-5}, 5.23×10^{-3}, 0.61504, 100)
9×10^{13}	(3.10×10^{-7}, 4.47×10^{-5}, 0.00449, 180)	9×10^{15}	(2.46×10^{-5}, 3.55×10^{-3}, 0.39006, 40)
1×10^{14}	(3.44×10^{-7}, 4.96×10^{-5}, 0.00499, 160)	1×10^{16}	(2.82×10^{-5}, 4.07×10^{-3}, 0.52004, 80)
2×10^{14}	(6.88×10^{-7}, 9.92×10^{-5}, 0.00997, 80)	2×10^{16}	(5.59×10^{-5}, 8.06×10^{-3}, 0.85005, 10)
3×10^{14}	(1.03×10^{-6}, 1.49×10^{-4}, 0.01495, 60)	3×10^{16}	(8.15×10^{-5}, 1.18×10^{-2}, 1.24076, 10)
4×10^{14}	(1.33×10^{-6}, 1.92×10^{-4}, 0.01933, 60)	4×10^{16}	(1.07×10^{-4}, 1.55×10^{-2}, 1.82445, 20)
5×10^{14}	(1.59×10^{-6}, 2.29×10^{-4}, 0.02326, 160)	5×10^{16}	(1.27×10^{-4}, 1.83×10^{-2}, 2.10081, 10)
6×10^{14}	(2.41×10^{-6}, 3.48×10^{-4}, 0.03574, 200)	1×10^{17}	(2.30×10^{-4}, 3.32×10^{-2}, 3.82767, 20)
7×10^{14}	(4.41×10^{-6}, 6.35×10^{-4}, 0.06481, 120)		

Table 17: Nuclide components of the target for producing ^{99}Mo.

isotopes	Number density (at/b-cm)
^{235}U	2.0577×10^{21}
^{238}U	1.5293×10^{20}
^{27}Al	5.6610×10^{22}

3.9 Molybdenum-99 (^{99}Mo)

^{99}Mo undergoes β^- decay with a half-life of 66 hours and a maximum ray energy of 0.437 MeV. ^{99}Mo is produced by in-reactor irradiation of Uranium-235 (^{235}U) through nuclei transmutation of $^{235}_{92}U(n,f)^{99}_{42}Mo$. The nuclide components of the target are shown in Table 17. The theoretical yield limits of ^{99}Mo under different neutron fluxes are given in Table 18.

3.10 Iodine-125 (^{125}I)

^{125}I undergoes electron capture with a half-life of 59.7 days, releasing a γ-ray with an energy of 35.50 keV and X-rays with energies of 27.20 keV and 27.47 keV. ^{125}I is produced by in-reactor irradiation of Xenon-124 (^{124}Xe) through nuclei transmutation of $^{124}_{54}Xe(n,\gamma)^{125}_{54}Xe \xrightarrow{\beta^-,\ 18h} {}^{125}_{53}I$. The nuclide components of the target are shown in Table 19. The theoretical yield limits of ^{125}I under different neutron fluxes are given in Table 20.

Table 18: Theoretical yield limits of ^{99}Mo under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	$(2.70\times10^{-8}, 1.31\times10^{-5}, 16.57, 40)$	8×10^{14}	$(1.31\times10^{-5}, 6.36\times10^{-3}, 16.13, 10)$
5×10^{12}	$(1.33\times10^{-7}, 6.45\times10^{-5}, 16.57, 160)$	9×10^{14}	$(1.39\times10^{-5}, 6.78\times10^{-3}, 16.05, 5)$
1×10^{13}	$(5.30\times10^{-7}, 2.57\times10^{-4}, 16.56, 20)$	1×10^{15}	$(1.74\times10^{-5}, 8.45\times10^{-3}, 15.96, 10)$
2×10^{13}	$(5.29\times10^{-7}, 2.57\times10^{-4}, 16.56, 80)$	2×10^{15}	$(2.72\times10^{-5}, 1.32\times10^{-2}, 15.33, 5)$
3×10^{13}	$(8.12\times10^{-7}, 3.95\times10^{-4}, 16.55, 60)$	3×10^{15}	$(3.24\times10^{-5}, 1.58\times10^{-2}, 14.90, 5)$
4×10^{13}	$(9.41\times10^{-7}, 4.57\times10^{-4}, 16.55, 10)$	4×10^{15}	$(3.64\times10^{-5}, 1.77\times10^{-2}, 14.37, 5)$
5×10^{13}	$(1.10\times10^{-6}, 5.36\times10^{-4}, 16.54, 20)$	5×10^{15}	$(3.82\times10^{-5}, 1.86\times10^{-2}, 14.09, 5)$
6×10^{13}	$(1.34\times10^{-6}, 6.50\times10^{-4}, 16.54, 20)$	6×10^{15}	$(3.96\times10^{-5}, 1.93\times10^{-2}, 13.61, 5)$
7×10^{13}	$(1.78\times10^{-6}, 8.66\times10^{-4}, 16.53, 10)$	7×10^{15}	$(4.09\times10^{-5}, 1.99\times10^{-2}, 12.73, 5)$
8×10^{13}	$(2.09\times10^{-6}, 1.02\times10^{-3}, 16.50, 5)$	8×10^{15}	$(4.08\times10^{-5}, 1.98\times10^{-2}, 12.82, 5)$
9×10^{13}	$(2.01\times10^{-6}, 9.78\times10^{-4}, 16.52, 10)$	9×10^{15}	$(4.15\times10^{-5}, 2.02\times10^{-2}, 13.54, 5)$
1×10^{14}	$(2.31\times10^{-6}, 1.12\times10^{-3}, 16.51, 20)$	1×10^{16}	$(4.17\times10^{-5}, 2.03\times10^{-2}, 12.43, 5)$
2×10^{14}	$(4.29\times10^{-6}, 2.09\times10^{-3}, 16.46, 10)$	2×10^{16}	$(4.18\times10^{-5}, 2.03\times10^{-2}, 12.84, 5)$
3×10^{14}	$(5.98\times10^{-6}, 2.90\times10^{-3}, 16.42, 20)$	3×10^{16}	$(4.20\times10^{-5}, 2.04\times10^{-2}, 12.44, 5)$
4×10^{14}	$(8.17\times10^{-6}, 3.97\times10^{-3}, 16.30, 10)$	4×10^{16}	$(4.22\times10^{-5}, 2.05\times10^{-2}, 12.66, 5)$
5×10^{14}	$(9.48\times10^{-6}, 4.61\times10^{-3}, 16.30, 10)$	5×10^{16}	$(4.30\times10^{-5}, 2.09\times10^{-2}, 12.44, 5)$
6×10^{14}	$(1.04\times10^{-5}, 5.06\times10^{-3}, 16.20, 5)$	1×10^{17}	$(4.45\times10^{-5}, 2.16\times10^{-2}, 12.06, 5)$
7×10^{14}	$(1.30\times10^{-5}, 6.32\times10^{-3}, 16.17, 10)$		

Table 19: Nuclide components of the target for producing ^{125}I.

isotopes	Number density (at/b-cm)
^{124}Xe	2.8624×10^{19}
^{132}Xe	2.6891×10^{15}

Table 20: Theoretical yield limits of ^{125}I under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	$(1.86\times10^{-9}, 6.51\times10^{-5}, 99.99, 20)$	8×10^{14}	$(9.20\times10^{-7}, 3.21\times10^{-2}, 94.83, 5)$
5×10^{12}	$(9.28\times10^{-9}, 3.24\times10^{-4}, 99.97, 20)$	9×10^{14}	$(9.96\times10^{-7}, 3.48\times10^{-2}, 94.16, 5)$
1×10^{13}	$(1.84\times10^{-8}, 6.44\times10^{-4}, 99.94, 20)$	1×10^{15}	$(1.07\times10^{-6}, 3.73\times10^{-2}, 93.58, 5)$
2×10^{13}	$(2.90\times10^{-8}, 1.01\times10^{-3}, 99.87, 5)$	2×10^{15}	$(1.84\times10^{-6}, 6.43\times10^{-2}, 87.29, 5)$
3×10^{13}	$(4.77\times10^{-8}, 1.67\times10^{-3}, 99.81, 40)$	3×10^{15}	$(2.36\times10^{-6}, 8.24\times10^{-2}, 80.79, 5)$
4×10^{13}	$(6.02\times10^{-8}, 2.10\times10^{-3}, 99.74, 5)$	4×10^{15}	$(2.53\times10^{-6}, 8.83\times10^{-2}, 75.91, 5)$
5×10^{13}	$(6.70\times10^{-8}, 2.34\times10^{-3}, 99.68, 5)$	5×10^{15}	$(2.67\times10^{-6}, 9.33\times10^{-2}, 68.18, 5)$
6×10^{13}	$(8.17\times10^{-8}, 2.85\times10^{-3}, 99.61, 5)$	6×10^{15}	$(2.68\times10^{-6}, 9.36\times10^{-2}, 60.16, 5)$
7×10^{13}	$(9.52\times10^{-8}, 3.33\times10^{-3}, 99.55, 5)$	7×10^{15}	$(2.67\times10^{-6}, 9.33\times10^{-2}, 58.05, 5)$
8×10^{13}	$(1.54\times10^{-7}, 5.38\times10^{-3}, 99.48, 5)$	8×10^{15}	$(2.69\times10^{-6}, 9.39\times10^{-2}, 54.62, 5)$
9×10^{13}	$(1.49\times10^{-7}, 5.19\times10^{-3}, 99.42, 5)$	9×10^{15}	$(2.69\times10^{-6}, 9.40\times10^{-2}, 50.27, 5)$
1×10^{14}	$(1.30\times10^{-7}, 4.55\times10^{-3}, 99.35, 10)$	1×10^{16}	$(2.69\times10^{-6}, 9.40\times10^{-2}, 49.58, 5)$
2×10^{14}	$(2.64\times10^{-7}, 9.24\times10^{-3}, 98.70, 10)$	2×10^{16}	$(2.66\times10^{-6}, 9.28\times10^{-2}, 28.01, 5)$
3×10^{14}	$(4.38\times10^{-7}, 1.53\times10^{-2}, 98.06, 10)$	3×10^{16}	$(2.63\times10^{-6}, 9.20\times10^{-2}, 25.12, 5)$
4×10^{14}	$(5.67\times10^{-7}, 1.98\times10^{-2}, 97.42, 10)$	4×10^{16}	$(2.66\times10^{-6}, 9.30\times10^{-2}, 35.04, 5)$
5×10^{14}	$(6.54\times10^{-7}, 2.29\times10^{-2}, 96.79, 10)$	5×10^{16}	$(2.68\times10^{-6}, 9.37\times10^{-2}, 15.92, 5)$
6×10^{14}	$(7.12\times10^{-7}, 2.49\times10^{-2}, 96.06, 5)$	1×10^{17}	$(2.67\times10^{-6}, 9.34\times10^{-2}, 19.17, 5)$
7×10^{14}	$(7.84\times10^{-7}, 2.74\times10^{-2}, 95.44, 5)$		

Table 21: Nuclide components of the target for producing ^{131}I.

isotopes	Number density (at/b-cm)	isotopes	Number density (at/b-cm)	isotopes	Number density (at/b-cm)
^{120}Te	2.0677×10^{19}	^{23}Na	4.4557×10^{19}	^{114}Cd	9.5302×10^{16}
^{122}Te	5.6000×10^{20}	^{88}Sr	1.1653×10^{18}	^{203}Tl	1.6823×10^{17}
^{124}Te	1.0373×10^{21}	^{31}P	1.1024×10^{16}	^{24}Mg	4.2708×10^{17}
^{125}Te	1.5378×10^{21}	^{56}Fe	6.1045×10^{18}	^{40}Ca	8.5443×10^{17}
^{126}Te	4.0815×10^{21}	^{110}Cd	4.2940×10^{16}	^{120}Sn	8.5433×10^{16}
^{128}Te	6.8253×10^{21}	^{111}Cd	4.3608×10^{16}	^{63}Cu	1.6278×10^{17}
^{130}Te	7.2795×10^{21}	^{112}Cd	8.1474×10^{16}	^{137}Ba	3.3773×10^{17}
^{16}O	4.3056×10^{22}	^{113}Cd	4.0896×10^{16}	^{138}Ba	2.1407×10^{18}
^{27}Al	1.2655×10^{18}				

3.11 Iodine-131 (^{131}I)

^{131}I undergoes β^- decay with a half-life of 8.02 days and a maximum ray energy of 0.606 MeV. ^{131}I is produced by in-reactor irradiation of Tellurium dioxide through nuclei transmutation of $^{130}_{52}Te(n,\gamma)^{131}_{52}Te\xrightarrow{\beta^-,\,25mins}{}^{131}_{53}I$. The nuclide components of the target are shown in Table 21. The theoretical yield limits of ^{131}I are given in Table 22.

3.12 Samarium-153 (^{153}Sm)

^{153}Sm undergoes β^- decay with a half-life of 46.3 hours and an average ray energy of 0.224 MeV. ^{153}Sm is produced by in-reactor irradiation of Samarium sesquioxide (Sm_2O_3) through nuclei transmutation of $^{152}_{62}Sm(n,\gamma)^{153}_{62}Sm$. The nuclide components of the target are shown in Table 23. The theoretical yield limits of ^{153}Sm under different neutron fluxes are given in Table 24.

Table 22: Theoretical yield limits of ^{131}I under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	(1.56×10^{-9}, 2.15×10^{-7}, 16.14, 120)	8×10^{14}	(1.24×10^{-6}, 1.70×10^{-4}, 24.24, 40)
5×10^{12}	(9.54×10^{-9}, 1.31×10^{-6}, 16.14, 120)	9×10^{14}	(1.84×10^{-6}, 2.53×10^{-4}, 22.55, 120)
1×10^{13}	(1.52×10^{-8}, 2.09×10^{-6}, 16.14, 140)	1×10^{15}	(1.87×10^{-6}, 2.57×10^{-4}, 28.73, 180)
2×10^{13}	(3.28×10^{-8}, 4.50×10^{-6}, 25.80, 180)	2×10^{15}	(3.42×10^{-6}, 4.70×10^{-4}, 19.01, 200)
3×10^{13}	(4.56×10^{-8}, 6.26×10^{-6}, 26.46, 200)	3×10^{15}	(4.86×10^{-6}, 6.67×10^{-4}, 16.88, 200)
4×10^{13}	(6.81×10^{-8}, 9.35×10^{-6}, 26.29, 180)	4×10^{15}	(4.59×10^{-6}, 6.30×10^{-4}, 26.68, 80)
5×10^{13}	(8.72×10^{-8}, 1.20×10^{-5}, 21.70, 180)	5×10^{15}	(5.87×10^{-6}, 8.06×10^{-4}, 22.26, 80)
6×10^{13}	(8.87×10^{-8}, 1.22×10^{-5}, 21.42, 60)	6×10^{15}	(6.13×10^{-6}, 8.42×10^{-4}, 11.58, 120)
7×10^{13}	(1.09×10^{-7}, 1.50×10^{-5}, 25.27, 80)	7×10^{15}	(7.30×10^{-6}, 1.00×10^{-3}, 25.49, 100)
8×10^{13}	(1.34×10^{-7}, 1.85×10^{-5}, 16.58, 100)	8×10^{15}	(8.39×10^{-6}, 1.15×10^{-3}, 20.40, 180)
9×10^{13}	(1.40×10^{-7}, 1.93×10^{-5}, 24.29, 60)	9×10^{15}	(1.04×10^{-5}, 1.42×10^{-3}, 22.47, 80)
1×10^{14}	(1.60×10^{-7}, 2.20×10^{-5}, 25.16, 200)	1×10^{16}	(8.78×10^{-6}, 1.21×10^{-3}, 14.25, 20)
2×10^{14}	(3.26×10^{-7}, 4.48×10^{-5}, 28.37, 180)	2×10^{16}	(1.38×10^{-5}, 1.90×10^{-3}, 14.76, 80)
3×10^{14}	(8.75×10^{-7}, 1.20×10^{-4}, 17.42, 120)	3×10^{16}	(1.99×10^{-5}, 2.74×10^{-3}, 19.61, 20)
4×10^{14}	(7.62×10^{-7}, 1.05×10^{-4}, 16.52, 20)	4×10^{16}	(2.18×10^{-5}, 2.99×10^{-3}, 31.82, 60)
5×10^{14}	(8.93×10^{-7}, 1.23×10^{-4}, 12.36, 160)	5×10^{16}	(3.31×10^{-5}, 4.55×10^{-3}, 29.55, 100)
6×10^{14}	(1.01×10^{-6}, 1.39×10^{-4}, 23.00, 120)	1×10^{17}	(7.96×10^{-5}, 1.09×10^{-2}, 25.12, 160)
7×10^{14}	(1.66×10^{-6}, 2.27×10^{-4}, 19.90, 40)		

Table 23: Nuclide components of the target for producing ^{153}Sm.

isotopes	Number density (at/b-cm)	isotopes	Number density (at/b-cm)	isotopes	Number density (at/b-cm)
^{144}Sm	5.0861×10^{19}	^{154}Sm	1.5017×10^{20}	^{51}V	9.8705×10^{15}
^{147}Sm	1.0489×10^{20}	^{16}O	7.3522×10^{22}	^{56}Zn	7.7444×10^{15}
^{148}Sm	7.8134×10^{19}	^{56}Fe	4.4949×10^{16}	^{55}Mn	1.8306×10^{16}
^{149}Sm	8.0195×10^{19}	^{28}Si	6.2906×10^{17}	^{63}Cu	1.5981×10^{16}
^{150}Sm	5.1394×10^{19}	^{59}Co	8.5324×10^{15}	^{24}Mg	4.1930×10^{16}
^{152}Sm	2.4851×10^{22}	^{52}Cr	9.6812×10^{15}	^{40}Ca	5.6623×10^{17}

Table 24: Theoretical yield limits of ^{153}Sm under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	(3.22×10^{-6}, 1.30×10^{-4}, 0.01, 10)	8×10^{14}	(1.57×10^{-3}, 6.33×10^{-2}, 7.51, 5)
5×10^{12}	(2.92×10^{-5}, 1.18×10^{-3}, 0.12, 180)	9×10^{14}	(2.12×10^{-3}, 8.54×10^{-2}, 10.94%, 5)
1×10^{13}	(3.71×10^{-5}, 1.49×10^{-3}, 0.15, 80)	1×10^{15}	(2.01×10^{-3}, 8.10×10^{-2}, 10.08%, 5)
2×10^{13}	(6.16×10^{-5}, 2.48×10^{-3}, 0.27, 40)	2×10^{15}	(3.44×10^{-3}, 1.38×10^{-1}, 17.86%, 5)
3×10^{13}	(9.81×10^{-5}, 3.95×10^{-3}, 0.43, 10)	3×10^{15}	(4.42×10^{-3}, 1.78×10^{-1}, 29.34%, 5)
4×10^{13}	(1.16×10^{-4}, 4.67×10^{-3}, 0.57, 100)	4×10^{15}	(6.55×10^{-3}, 2.64×10^{-1}, 45.30%, 5)
5×10^{13}	(1.40×10^{-4}, 5.62×10^{-3}, 0.58, 20)	5×10^{15}	(6.79×10^{-3}, 2.73×10^{-1}, 54.28%, 5)
6×10^{13}	(1.78×10^{-4}, 7.16×10^{-3}, 0.82, 10)	6×10^{15}	(6.90×10^{-3}, 2.78×10^{-1}, 57.88%, 5)
7×10^{13}	(1.94×10^{-4}, 7.82×10^{-3}, 0.79, 20)	7×10^{15}	(5.89×10^{-3}, 2.37×10^{-1}, 40.45%, 5)
8×10^{13}	(2.46×10^{-4}, 9.91×10^{-3}, 1.06, 10)	8×10^{15}	(5.47×10^{-3}, 2.20×10^{-1}, 44.05%, 5)
9×10^{13}	(2.65×10^{-4}, 1.07×10^{-2}, 1.21, 40)	9×10^{15}	(5.50×10^{-3}, 2.21×10^{-1}, 36.51%, 5)
1×10^{14}	(2.54×10^{-4}, 1.02×10^{-2}, 1.57, 20)	1×10^{16}	(5.99×10^{-3}, 2.41×10^{-1}, 49.21%, 5)
2×10^{14}	(5.27×10^{-4}, 2.12×10^{-2}, 2.18, 10)	2×10^{16}	(5.81×10^{-3}, 2.34×10^{-1}, 42.93%, 5)
3×10^{14}	(7.88×10^{-4}, 3.17×10^{-2}, 3.36, 10)	3×10^{16}	(5.23×10^{-3}, 2.10×10^{-1}, 63.61%, 5)
4×10^{14}	(1.16×10^{-3}, 4.67×10^{-2}, 5.22, 10)	4×10^{16}	(5.51×10^{-3}, 2.22×10^{-1}, 49.86%, 5)
5×10^{14}	(1.12×10^{-3}, 4.49×10^{-2}, 6.60, 20)	5×10^{16}	(6.62×10^{-3}, 2.66×10^{-1}, 45.16%, 5)
6×10^{14}	(1.31×10^{-3}, 5.28×10^{-2}, 6.15, 10)	1×10^{17}	(5.13×10^{-3}, 2.06×10^{-1}, 30.46%, 5)
7×10^{14}	(1.44×10^{-3}, 5.78×10^{-2}, 7.18, 5)		

Table 25: Nuclide components of the target for producing ^{161}Tb.

isotopes	Number density (at/b-cm)	isotopes	Number density (at/b-cm)
^{160}Gd	2.3765×10^{22}	^{155}Gd	5.9957×10^{19}
^{158}Gd	2.0831×10^{20}	^{154}Gd	1.0058×10^{19}
^{157}Gd	6.6591×10^{19}	^{16}O	3.6926×10^{22}
^{156}Gd	9.6805×10^{19}		

3.13 Terbium-161 (^{161}Tb)

^{161}Tb undergoes β^- decay with a half-life of 6.9 days and an average ray energy of 0.154 MeV. ^{161}Tb is produced by in-reactor irradiation of Gadolinium oxide (Gd_2O_3) through nuclei transmutation of $^{160}_{64}Gd(n,\gamma)^{161}_{64}Gd \xrightarrow{\beta^-,\ 3.7mins} {}^{161}_{65}Tb$. The nuclide components of the target are shown in Table 25. The theoretical yield limits of ^{161}Tb under different neutron fluxes are given in Table 26.

3.14 Holmium-166 (^{166}Ho)

^{166}Ho undergoes β^- decay with a half-life of 26.8 hours and an average ray energy of 0.666 MeV. ^{166}Ho is produced by in-reactor irradiation of $Dy(NO_3)_3\cdot5H_2O$ through nuclei transmutation of $^{164}_{66}Dy(n,\gamma)^{165}_{66}Dy(n,\gamma)^{166}_{66}Dy \xrightarrow{\beta^-,\ 81.6h} {}^{166}_{67}Ho$. The nuclide components of the target are shown in Table 27. The theoretical yield limits of ^{166}Ho under different neutron fluxes are given in Table 28.

Table 26: Theoretical yield limits of ^{161}Tb under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	$(3.988\times10^{-8}, 1.68\times10^{-6}, 92.40, 200)$	8×10^{14}	$(3.257\times10^{-5}, 1.37\times10^{-3}, 92.05, 60)$
5×10^{12}	$(2.139\times10^{-7}, 9.00\times10^{-6}, 97.21, 80)$	9×10^{14}	$(4.092\times10^{-5}, 1.72\times10^{-3}, 92.69, 200)$
1×10^{13}	$(3.788\times10^{-7}, 1.59\times10^{-5}, 97.69, 120)$	1×10^{15}	$(3.102\times10^{-5}, 1.31\times10^{-3}, 93.80, 120)$
2×10^{13}	$(7.493\times10^{-7}, 3.15\times10^{-5}, 93.48, 180)$	2×10^{15}	$(9.343\times10^{-5}, 3.93\times10^{-3}, 92.85, 160)$
3×10^{13}	$(1.135\times10^{-6}, 4.78\times10^{-5}, 94.59, 200)$	3×10^{15}	$(8.546\times10^{-5}, 3.60\times10^{-3}, 95.21, 140)$
4×10^{13}	$(1.483\times10^{-6}, 6.24\times10^{-5}, 95.15, 140)$	4×10^{15}	$(8.657\times10^{-5}, 3.64\times10^{-3}, 89.16, 60)$
5×10^{13}	$(1.942\times10^{-6}, 8.17\times10^{-5}, 95.03, 140)$	5×10^{15}	$(1.046\times10^{-4}, 4.40\times10^{-3}, 94.03, 80)$
6×10^{13}	$(2.383\times10^{-6}, 1.00\times10^{-4}, 94.14, 140)$	6×10^{15}	$(1.067\times10^{-4}, 4.49\times10^{-3}, 89.93, 60)$
7×10^{13}	$(2.920\times10^{-6}, 1.23\times10^{-4}, 93.78, 80)$	7×10^{15}	$(1.817\times10^{-4}, 7.64\times10^{-3}, 94.65, 200)$
8×10^{13}	$(3.699\times10^{-6}, 1.56\times10^{-4}, 93.80, 100)$	8×10^{15}	$(2.054\times10^{-4}, 8.64\times10^{-3}, 88.51, 120)$
9×10^{13}	$(3.299\times10^{-6}, 1.39\times10^{-4}, 95.39, 160)$	9×10^{15}	$(3.059\times10^{-4}, 1.29\times10^{-2}, 90.16, 80)$
1×10^{14}	$(5.132\times10^{-6}, 2.16\times10^{-4}, 94.22, 10)$	1×10^{16}	$(2.399\times10^{-4}, 1.01\times10^{-2}, 94.81, 80)$
2×10^{14}	$(8.459\times10^{-6}, 3.56\times10^{-4}, 95.14, 60)$	2×10^{16}	$(3.868\times10^{-4}, 1.63\times10^{-2}, 92.43, 60)$
3×10^{14}	$(1.873\times10^{-5}, 7.88\times10^{-4}, 92.50, 100)$	3×10^{16}	$(4.806\times10^{-4}, 2.02\times10^{-2}, 91.15, 100)$
4×10^{14}	$(1.905\times10^{-5}, 8.01\times10^{-4}, 93.19, 40)$	4×10^{16}	$(7.244\times10^{-4}, 3.05\times10^{-2}, 94.94, 60)$
5×10^{14}	$(1.811\times10^{-5}, 7.62\times10^{-4}, 94.49, 180)$	5×10^{16}	$(7.147\times10^{-4}, 3.01\times10^{-2}, 91.26, 80)$
6×10^{14}	$(2.664\times10^{-5}, 1.12\times10^{-3}, 95.01, 180)$	1×10^{17}	$(1.011\times10^{-3}, 4.25\times10^{-2}, 43.49, 20)$
7×10^{14}	$(2.291\times10^{-5}, 9.64\times10^{-4}, 95.37, 80)$		

Table 27: Nuclide components of the target for producing ^{166}Ho.

isotopes	Number density (at/b-cm)	isotopes	Number density (at/b-cm)
^{156}Dy	2.43×10^{18}	^{163}Dy	9.65×10^{20}
^{158}Dy	4.00×10^{18}	^{164}Dy	1.09×10^{21}
^{160}Dy	9.24×10^{19}	^{14}N	1.17×10^{22}
^{161}Dy	7.42×10^{20}	^{16}O	5.44×10^{22}
^{162}Dy	9.95×10^{20}	^{1}H	3.89×10^{17}

Table 28: Theoretical yield limits of ^{166}Ho under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	(1.09×10^{-11}, 9.96×10^{-9}, 0.002, 100)	8×10^{14}	(2.62×10^{-6}, 2.40×10^{-3}, 1.916, 5)
5×10^{12}	(2.47×10^{-10}, 2.26×10^{-7}, 0.009, 80)	9×10^{14}	(2.96×10^{-6}, 2.71×10^{-3}, 4.091, 5)
1×10^{13}	(9.31×10^{-10}, 8.54×10^{-7}, 0.024, 20)	1×10^{15}	(3.51×10^{-6}, 3.22×10^{-3}, 1.437, 5)
2×10^{13}	(3.39×10^{-9}, 3.11×10^{-6}, 0.075, 20)	2×10^{15}	(1.00×10^{-5}, 9.18×10^{-3}, 6.263, 5)
3×10^{13}	(8.39×10^{-9}, 7.70×10^{-6}, 0.071, 20)	3×10^{15}	(1.85×10^{-5}, 1.70×10^{-2}, 6.661, 5)
4×10^{13}	(1.32×10^{-8}, 1.21×10^{-5}, 0.144, 20)	4×10^{15}	(2.47×10^{-5}, 2.26×10^{-2}, 22.648, 5)
5×10^{13}	(2.15×10^{-8}, 1.97×10^{-5}, 0.095, 20)	5×10^{15}	(3.36×10^{-5}, 3.09×10^{-2}, 16.286, 5)
6×10^{13}	(2.98×10^{-8}, 2.73×10^{-5}, 0.214, 20)	6×10^{15}	(4.24×10^{-5}, 3.89×10^{-2}, 16.392, 10)
7×10^{13}	(3.76×10^{-8}, 3.45×10^{-5}, 0.265, 10)	7×10^{15}	(5.51×10^{-5}, 5.05×10^{-2}, 36.384, 5)
8×10^{13}	(6.63×10^{-8}, 6.08×10^{-5}, 0.437, 10)	8×10^{15}	(6.78×10^{-5}, 6.22×10^{-2}, 17.119, 5)
9×10^{13}	(5.84×10^{-8}, 5.36×10^{-5}, 0.305, 20)	9×10^{15}	(8.09×10^{-5}, 7.42×10^{-2}, 16.423, 5)
1×10^{14}	(7.32×10^{-8}, 6.71×10^{-5}, 0.346, 10)	1×10^{16}	(9.13×10^{-5}, 8.37×10^{-2}, 60.027, 5)
2×10^{14}	(2.72×10^{-7}, 2.50×10^{-4}, 1.093, 10)	2×10^{16}	(2.35×10^{-4}, 2.16×10^{-1}, 30.554, 5)
3×10^{14}	(5.34×10^{-7}, 4.90×10^{-4}, 0.695, 10)	3×10^{16}	(3.50×10^{-4}, 3.21×10^{-1}, 44.113, 5)
4×10^{14}	(8.22×10^{-7}, 7.54×10^{-4}, 0.908, 10)	4×10^{16}	(4.44×10^{-4}, 4.07×10^{-1}, 58.776, 5)
5×10^{14}	(1.19×10^{-6}, 1.09×10^{-3}, 0.870, 10)	5×10^{16}	(5.23×10^{-4}, 4.80×10^{-1}, 71.302, 5)
6×10^{14}	(1.61×10^{-6}, 1.48×10^{-3}, 3.509, 5)	1×10^{17}	(8.03×10^{-4}, 7.37×10^{-1}, 72.235, 5)
7×10^{14}	(2.08×10^{-6}, 1.91×10^{-3}, 1.804, 5)		

Table 29: Nuclide components of the target for producing ^{177}Lu.

isotopes	Number density (at/b-cm)
^{176}Lu	2.3250×10^{22}
^{175}Lu	5.1329×10^{21}
^{16}O	4.2772×10^{22}

3.15 Lutetium-177 (^{177}Lu)

^{177}Lu undergoes β^- decay with a half-life of 6.7 days and an average ray energy of 0.497 MeV. ^{177}Lu is produced by in-reactor irradiation of Lutetium oxide (Lu_2O_3) through nuclei transmutation of $^{176}_{71}Lu(n,\gamma)^{177}_{71}Lu$. The nuclide components of the target are shown in Table 29. The theoretical yield limits of ^{177}Lu under different neutron fluxes are given in Table 30.

3.16 Rhenium-186 (^{186}Re)

^{186}Re undergoes β^- decay with a half-life of 3.72 days and average ray energies of 1.07 MeV (77%) and 0.93 MeV (23%). ^{186}Re is produced by in-reactor irradiation of Rhenium metal through nuclei transmutation of $^{185}_{75}\mathrm{Re}(n,\gamma)^{186}_{75}\mathrm{Re}$. The nuclide components of the target are shown in Table 31. The theoretical yield limits of ^{186}Re under different neutron fluxes are given in Table 32.

Table 30: Theoretical yield limits of ^{177}Lu under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	$(4.14E^{-5}, 1.78E^{-3}, 0.15, 180)$	8×10^{14}	$(9.03E^{-3}, 3.88E^{-1}, 47.33, 10)$
5×10^{12}	$(2.42E^{-4}, 1.04E^{-2}, 0.99, 160)$	9×10^{14}	$(9.27E^{-3}, 3.99E^{-1}, 50.58, 10)$
1×10^{13}	$(3.96E^{-4}, 1.70E^{-2}, 1.46, 40)$	1×10^{15}	$(9.34E^{-3}, 4.02E^{-1}, 52.73, 5)$
2×10^{13}	$(6.57E^{-4}, 2.83E^{-2}, 3.17, 100)$	2×10^{15}	$(1.23E^{-2}, 5.29E^{-1}, 62.27, 5)$
3×10^{13}	$(1.03E^{-3}, 4.43E^{-2}, 4.18, 40)$	3×10^{15}	$(1.24E^{-2}, 5.35E^{-1}, 74.58, 5)$
4×10^{13}	$(1.56E^{-3}, 6.72E^{-2}, 6.51, 20)$	4×10^{15}	$(1.18E^{-2}, 5.10E^{-1}, 72.99, 5)$
5×10^{13}	$(1.56E^{-3}, 6.69E^{-2}, 6.93, 40)$	5×10^{15}	$(1.13E^{-2}, 4.86E^{-1}, 73.36, 5)$
6×10^{13}	$(1.61E^{-3}, 6.93E^{-2}, 8.06, 40)$	6×10^{15}	$(1.12E^{-2}, 4.83E^{-1}, 74.31, 5)$
7×10^{13}	$(2.13E^{-3}, 9.14E^{-2}, 9.51, 20)$	7×10^{15}	$(1.04E^{-2}, 4.49E^{-1}, 77.08, 5)$
8×10^{13}	$(2.54E^{-3}, 1.09E^{-1}, 10.83, 10)$	8×10^{15}	$(9.57E^{-3}, 4.12E^{-1}, 64.25, 5)$
9×10^{13}	$(2.60E^{-3}, 1.12E^{-1}, 12.26, 10)$	9×10^{15}	$(9.25E^{-3}, 3.98E^{-1}, 66.76, 5)$
1×10^{14}	$(2.75E^{-3}, 1.18E^{-1}, 11.80, 20)$	1×10^{16}	$(8.50E^{-3}, 3.65E^{-1}, 66.19, 5)$
2×10^{14}	$(4.26E^{-3}, 1.83E^{-1}, 20.52, 20)$	2×10^{16}	$(5.62E^{-3}, 2.42E^{-1}, 57.03, 5)$
3×10^{14}	$(5.26E^{-3}, 2.26E^{-1}, 27.93, 10)$	3×10^{16}	$(3.80E^{-3}, 1.64E^{-1}, 36.07, 5)$
4×10^{14}	$(6.85E^{-3}, 2.95E^{-1}, 34.69, 5)$	4×10^{16}	$(2.86E^{-3}, 1.23E^{-1}, 28.80, 5)$
5×10^{14}	$(7.27E^{-3}, 3.12E^{-1}, 37.80, 10)$	5×10^{16}	$(2.25E^{-3}, 9.69E^{-2}, 23.41, 5)$
6×10^{14}	$(7.63E^{-3}, 3.28E^{-1}, 38.34, 5)$	1×10^{17}	$(1.04E^{-3}, 4.47E^{-2}, 10.79, 5)$
7×10^{14}	$(9.23E^{-3}, 3.97E^{-1}, 48.65, 10)$		

Table 31: Nuclide components of the target for producing ^{186}Re.

isotopes	Number density (at/b-cm)
^{185}Re	6.4875×10^{22}
^{187}Re	3.5919×10^{21}

Table 32: Theoretical yield limits of ^{186}Re under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	(1.42×10^{-5}, 2.20×10^{-4}, 0.02, 40)	8×10^{14}	(1.07×10^{-2}, 1.64×10^{-1}, 20.13, 10)
5×10^{12}	(7.62×10^{-5}, 1.17×10^{-3}, 0.11, 120)	9×10^{14}	(9.65×10^{-3}, 1.49×10^{-1}, 19.62, 10)
1×10^{13}	(1.53×10^{-4}, 2.35×10^{-3}, 0.23, 60)	1×10^{15}	(8.97×10^{-3}, 1.38×10^{-1}, 22.47, 10)
2×10^{13}	(3.44×10^{-4}, 5.31×10^{-3}, 0.62, 140)	2×10^{15}	(1.54×10^{-2}, 2.38×10^{-1}, 34.91, 5)
3×10^{13}	(4.71×10^{-4}, 7.26×10^{-3}, 0.95, 180)	3×10^{15}	(1.75×10^{-2}, 2.69×10^{-1}, 42.60, 5)
4×10^{13}	(5.94×10^{-4}, 9.15×10^{-3}, 0.89, 20)	4×10^{15}	(2.16×10^{-2}, 3.32×10^{-1}, 50.97, 5)
5×10^{13}	(7.37×10^{-4}, 1.14×10^{-2}, 1.27, 20)	5×10^{15}	(2.52×10^{-2}, 3.88×10^{-1}, 54.65, 5)
6×10^{13}	(8.78×10^{-4}, 1.35×10^{-2}, 1.52, 20)	6×10^{15}	(2.50×10^{-2}, 3.85×10^{-1}, 53.34, 5)
7×10^{13}	(9.04×10^{-4}, 1.39×10^{-2}, 1.54, 40)	7×10^{15}	(2.79×10^{-2}, 4.30×10^{-1}, 61.40, 5)
8×10^{13}	(1.03×10^{-3}, 1.59×10^{-2}, 2.03, 10)	8×10^{15}	(2.92×10^{-2}, 4.50×10^{-1}, 67.88, 5)
9×10^{13}	(1.16×10^{-3}, 1.78×10^{-2}, 1.94, 10)	9×10^{15}	(2.88×10^{-2}, 4.45×10^{-1}, 66.36, 5)
1×10^{14}	(1.28×10^{-3}, 1.98×10^{-2}, 2.28, 10)	1×10^{16}	(2.88×10^{-2}, 4.44×10^{-1}, 66.07, 5)
2×10^{14}	(2.28×10^{-3}, 3.51×10^{-2}, 4.57, 20)	2×10^{16}	(2.70×10^{-2}, 4.16×10^{-1}, 65.33, 5)
3×10^{14}	(3.68×10^{-3}, 5.67×10^{-2}, 6.01, 10)	3×10^{16}	(2.48×10^{-2}, 3.82×10^{-1}, 60.62, 5)
4×10^{14}	(5.84×10^{-3}, 9.00×10^{-2}, 10.15, 10)	4×10^{16}	(2.28×10^{-2}, 3.52×10^{-1}, 54.72, 5)
5×10^{14}	(5.10×10^{-3}, 7.85×10^{-2}, 10.46, 10)	5×10^{16}	(2.11×10^{-2}, 3.25×10^{-1}, 48.05, 5)
6×10^{14}	(6.33×10^{-3}, 9.76×10^{-2}, 11.76, 10)	1×10^{17}	(1.47×10^{-2}, 2.27×10^{-1}, 32.58, 5)
7×10^{14}	(6.47×10^{-3}, 9.97×10^{-2}, 14.17, 10)		

Table 33: Nuclide components of the target for producing ^{188}Re.

isotopes	Number density (at/b-cm)
^{182}W	2.7600×10^{20}
^{183}W	1.4797×10^{20}
^{184}W	3.1568×10^{20}
^{186}W	1.7701×10^{22}
^{16}O	5.5321×10^{22}

3.17 Rhenium-188 (^{188}Re)

^{188}Re undergoes β^- decay with a half-life of 16.9 hours and an average ray energy of 0.76 MeV. ^{188}Re is produced by in-reactor irradiation of tungsten oxide (WO$_3$) through nuclei transmutation of $^{186}_{74}W(n,\gamma)^{187}_{74}W(n,\gamma)^{188}_{74}W \xrightarrow{\beta^-,\ 69.4h} {}^{188}_{75}\mathrm{Re}$. The nuclide components of the target are shown in Table 33. The theoretical yield limits of ^{188}Re under different neutron fluxes are given in Table 34.

3.18 Iridium-192 (^{192}Ir)

^{192}Ir undergoes β^- decay and electron capture with a half-life of 73.8 days and ray energies of 0.559 MeV (β^-) and 0.365 MeV (λ). ^{192}Ir is produced by in-reactor irradiation of sodium hexaehloroiridate (Na$_2$IrCl$_6$) through nuclei transmutation of $^{191}_{77}Ir(n,\gamma)^{192}_{77}Ir$. The nuclide components of the target are shown in Table 35. The theoretical yield limits of ^{192}Ir under different neutron fluxes are given in Table 36.

Table 34: Theoretical yield limits of ^{188}Re under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	$(1.02\times10^{-10}, 5.78\times10^{-9}, 0.0008, 200)$	8×10^{14}	$(2.52\times10^{-5}, 1.42\times10^{-3}, 1.6469, 100)$
5×10^{12}	$(2.54\times10^{-9}, 1.43\times10^{-7}, 0.0016, 200)$	9×10^{14}	$(3.11\times10^{-5}, 1.76\times10^{-3}, 1.8775, 40)$
1×10^{13}	$(1.00\times10^{-8}, 5.67\times10^{-7}, 0.0032, 200)$	1×10^{15}	$(3.45\times10^{-5}, 1.95\times10^{-3}, 2.0551, 60)$
2×10^{13}	$(3.91\times10^{-8}, 2.21\times10^{-6}, 0.0345, 200)$	2×10^{15}	$(8.82\times10^{-5}, 4.98\times10^{-3}, 3.7986, 60)$
3×10^{13}	$(8.54\times10^{-8}, 4.82\times10^{-6}, 0.0517, 200)$	3×10^{15}	$(1.58\times10^{-4}, 8.93\times10^{-3}, 5.4784, 40)$
4×10^{13}	$(1.49\times10^{-7}, 8.42\times10^{-6}, 0.0689, 200)$	4×10^{15}	$(2.08\times10^{-4}, 1.17\times10^{-2}, 3.3190, 40)$
5×10^{13}	$(2.23\times10^{-7}, 1.26\times10^{-5}, 0.0860, 200)$	5×10^{15}	$(2.77\times10^{-4}, 1.56\times10^{-2}, 9.3305, 20)$
6×10^{13}	$(3.53\times10^{-7}, 1.99\times10^{-5}, 0.1031, 200)$	6×10^{15}	$(3.35\times10^{-4}, 1.89\times10^{-2}, 12.8033, 20)$
7×10^{13}	$(4.68\times10^{-7}, 2.64\times10^{-5}, 0.1199, 200)$	7×10^{15}	$(3.95\times10^{-4}, 2.23\times10^{-2}, 12.2017, 20)$
8×10^{13}	$(5.98\times10^{-7}, 3.38\times10^{-5}, 0.1371, 200)$	8×10^{15}	$(4.62\times10^{-4}, 2.61\times10^{-2}, 11.3298, 20)$
9×10^{13}	$(7.02\times10^{-7}, 3.97\times10^{-5}, 0.1535, 200)$	9×10^{15}	$(5.29\times10^{-4}, 2.99\times10^{-2}, 16.2549, 20)$
1×10^{14}	$(8.40\times10^{-7}, 4.74\times10^{-5}, 0.1968, 180)$	1×10^{16}	$(5.90\times10^{-4}, 3.34\times10^{-2}, 14.8606, 20)$
2×10^{14}	$(2.79\times10^{-6}, 1.58\times10^{-4}, 0.2533, 180)$	2×10^{16}	$(1.21\times10^{-3}, 6.84\times10^{-2}, 25.7344, 10)$
3×10^{14}	$(6.01\times10^{-6}, 3.40\times10^{-4}, 0.5839, 120)$	3×10^{16}	$(1.81\times10^{-3}, 1.02\times10^{-1}, 43.9587, 10)$
4×10^{14}	$(8.70\times10^{-6}, 4.91\times10^{-4}, 0.7447, 160)$	4×10^{16}	$(2.30\times10^{-3}, 1.30\times10^{-1}, 23.7610, 10)$
5×10^{14}	$(1.30\times10^{-5}, 7.36\times10^{-4}, 0.8675, 120)$	5×10^{16}	$(2.75\times10^{-3}, 1.56\times10^{-1}, 27.7525, 5)$
6×10^{14}	$(1.66\times10^{-5}, 9.40\times10^{-4}, 1.4514, 80)$	1×10^{17}	$(4.83\times10^{-3}, 2.73\times10^{-1}, 74.9443, 5)$
7×10^{14}	$(2.10\times10^{-5}, 1.19\times10^{-3}, 1.1427, 100)$		

Table 35: Nuclide components of the target for producing ^{192}Ir.

isotopes	Number density (at/b-cm)
^{23}Na	1.0514×10^{22}
^{191}Ir	5.2570×10^{21}
^{35}Cl	3.1542×10^{22}

Table 36: Theoretical yield limits of ^{192}Ir under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	$(5.98\times10^{-5}, 1.14\times10^{-2}, 3.83, 200)$	8×10^{14}	$(2.78\times10^{-3}, 5.30\times10^{-1}, 78.24, 60)$
5×10^{12}	$(3.84\times10^{-4}, 7.31\times10^{-2}, 25.90, 200)$	9×10^{14}	$(2.82\times10^{-3}, 5.36\times10^{-1}, 80.72, 60)$
1×10^{13}	$(5.62\times10^{-4}, 1.07\times10^{-1}, 41.64, 200)$	1×10^{15}	$(3.12\times10^{-3}, 5.94\times10^{-1}, 75.16, 40)$
2×10^{13}	$(7.74\times10^{-4}, 1.47\times10^{-1}, 56.77, 180)$	2×10^{15}	$(3.65\times10^{-3}, 6.94\times10^{-1}, 81.65, 20)$
3×10^{13}	$(9.39\times10^{-4}, 1.79\times10^{-1}, 65.61, 200)$	3×10^{15}	$(3.94\times10^{-3}, 7.49\times10^{-1}, 76.23, 10)$
4×10^{13}	$(1.20\times10^{-3}, 2.28\times10^{-1}, 70.79, 200)$	4×10^{15}	$(3.95\times10^{-3}, 7.51\times10^{-1}, 65.54, 10)$
5×10^{13}	$(1.39\times10^{-3}, 2.65\times10^{-1}, 79.59, 60)$	5×10^{15}	$(3.73\times10^{-3}, 7.09\times10^{-1}, 62.34, 10)$
6×10^{13}	$(1.22\times10^{-3}, 2.33\times10^{-1}, 75.02, 120)$	6×10^{15}	$(3.72\times10^{-3}, 7.08\times10^{-1}, 55.29, 10)$
7×10^{13}	$(1.61\times10^{-3}, 3.05\times10^{-1}, 75.73, 20)$	7×10^{15}	$(3.44\times10^{-3}, 6.55\times10^{-1}, 47.41, 5)$
8×10^{13}	$(1.91\times10^{-3}, 3.64\times10^{-1}, 84.63, 100)$	8×10^{15}	$(3.74\times10^{-3}, 7.11\times10^{-1}, 45.43, 10)$
9×10^{13}	$(1.53\times10^{-3}, 2.91\times10^{-1}, 80.21, 160)$	9×10^{15}	$(3.32\times10^{-3}, 6.32\times10^{-1}, 36.47, 10)$
1×10^{14}	$(1.53\times10^{-3}, 2.90\times10^{-1}, 76.69, 120)$	1×10^{16}	$(3.44\times10^{-3}, 6.54\times10^{-1}, 37.44, 5)$
2×10^{14}	$(2.26\times10^{-3}, 4.31\times10^{-1}, 85.59, 80)$	2×10^{16}	$(3.58\times10^{-3}, 6.81\times10^{-1}, 9.71, 5)$
3×10^{14}	$(2.72\times10^{-3}, 5.17\times10^{-1}, 81.20, 40)$	3×10^{16}	$(3.21\times10^{-3}, 6.10\times10^{-1}, 4.03, 5)$
4×10^{14}	$(2.55\times10^{-3}, 4.86\times10^{-1}, 75.16, 80)$	4×10^{16}	$(2.84\times10^{-3}, 5.41\times10^{-1}, 4.46, 5)$
5×10^{14}	$(2.62\times10^{-3}, 4.98\times10^{-1}, 79.66, 80)$	5×10^{16}	$(2.51\times10^{-3}, 4.77\times10^{-1}, 6.25, 5)$
6×10^{14}	$(2.83\times10^{-3}, 5.38\times10^{-1}, 76.89, 20)$	1×10^{17}	$(1.26\times10^{-3}, 2.40\times10^{-1}, 0.58, 5)$
7×10^{14}	$(3.12\times10^{-3}, 5.94\times10^{-1}, 73.83, 40)$		

Table 37: Nuclide components of the target for producing ^{225}Ac.

isotopes	Number density (at/b-cm)
^{226}Ra	1.4654×10^{22}

3.19 Actinium-225 (^{225}Ac)

^{225}Ac undergoes α decay with a half-life of 9.92 years, releasing four α particles with energies of [5.8, 8.4] MeV and two β particles with energies of [1.6, 0.6] MeV. ^{225}Ac is produced by in-reactor irradiation of Radium-226 (^{226}Ra) through nuclei transmutation of $^{226}_{88}Ra(n,2n)^{225}_{88}Ra \xrightarrow{\beta^-,\,14.9d} {}^{225}_{89}Ac$. The nuclide components of the target are shown in Table 37. The theoretical yield limits of ^{225}Ac under different neutron fluxes are given in Table 38.

3.20 Californium-252 (^{252}Cf)

^{252}Cf releases continuous-energy neutrons with a half-life of 2.65 years. ^{252}Cf is produced by in-reactor irradiation of a mixture of plutonium, americium and curium through a complex nuclei transmutation chain.[20] The nuclide components of the target are shown in Table 39. The theoretical yield limits of ^{252}Cf are given in Table 40.

4. Conclusion

Medical isotopes are an important material basis for nuclear medicine and are currently facing a global shortage. In-reactor

Table 38: Theoretical yield limits of ^{225}Ac under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	(3.31×10^{-9}, 2.26×10^{-7}, 100.00, 60)	8×10^{14}	(2.34×10^{-6}, 1.60×10^{-4}, 100.00, 180)
5×10^{12}	(1.68×10^{-8}, 1.15×10^{-6}, 100.00, 180)	9×10^{14}	(6.95×10^{-6}, 4.75×10^{-4}, 100.00, 200)
1×10^{13}	(4.33×10^{-8}, 2.96×10^{-6}, 100.00, 60)	1×10^{15}	(5.63×10^{-6}, 3.84×10^{-4}, 100.00, 80)
2×10^{13}	(8.55×10^{-8}, 5.83×10^{-6}, 100.00, 160)	2×10^{15}	(2.08×10^{-5}, 1.42×10^{-3}, 100.00, 180)
3×10^{13}	(8.78×10^{-8}, 5.99×10^{-6}, 100.00, 60)	3×10^{15}	(2.21×10^{-5}, 1.51×10^{-3}, 100.00, 140)
4×10^{13}	(1.62×10^{-7}, 1.10×10^{-5}, 100.00, 200)	4×10^{15}	(3.58×10^{-5}, 2.44×10^{-3}, 100.00, 160)
5×10^{13}	(1.83×10^{-7}, 1.25×10^{-5}, 100.00, 200)	5×10^{15}	(4.84×10^{-5}, 3.31×10^{-3}, 100.00, 140)
6×10^{13}	(1.74×10^{-7}, 1.19×10^{-5}, 100.00, 80)	6×10^{15}	(4.52×10^{-5}, 3.08×10^{-3}, 100.00, 180)
7×10^{13}	(2.35×10^{-7}, 1.60×10^{-5}, 100.00, 160)	7×10^{15}	(6.20×10^{-5}, 4.23×10^{-3}, 100.00, 180)
8×10^{13}	(2.53×10^{-7}, 1.73×10^{-5}, 100.00, 160)	8×10^{15}	(1.22×10^{-4}, 8.32×10^{-3}, 100.00, 160)
9×10^{13}	(6.36×10^{-7}, 4.34×10^{-5}, 100.00, 100)	9×10^{15}	(2.15×10^{-4}, 1.47×10^{-2}, 100.00, 120)
1×10^{14}	(7.38×10^{-7}, 5.04×10^{-5}, 100.00, 160)	1×10^{16}	(1.44×10^{-4}, 9.79×10^{-3}, 100.00, 180)
2×10^{14}	(6.15×10^{-7}, 4.20×10^{-5}, 100.00, 140)	2×10^{16}	(5.95×10^{-4}, 4.06×10^{-2}, 100.00, 40)
3×10^{14}	(9.23×10^{-7}, 6.30×10^{-5}, 100.00, 120)	3×10^{16}	(3.91×10^{-4}, 2.67×10^{-2}, 100.00, 200)
4×10^{14}	(1.08×10^{-6}, 7.36×10^{-5}, 100.00, 80)	4×10^{16}	(8.76×10^{-4}, 5.98×10^{-2}, 100.00, 120)
5×10^{14}	(1.46×10^{-6}, 9.99×10^{-5}, 100.00, 140)	5×10^{16}	(6.01×10^{-4}, 4.10×10^{-2}, 100.00, 60)
6×10^{14}	(1.82×10^{-6}, 1.24×10^{-4}, 100.00, 160)	1×10^{17}	(8.67×10^{-4}, 5.92×10^{-2}, 100.00, 80)
7×10^{14}	(3.40×10^{-6}, 2.32×10^{-4}, 100.00, 100)		

Table 39: Nuclide components of the target for producing ^{252}Cf.

isotopes	Number density (at/b-cm)	isotopes	Number density (at/b-cm)	isotopes	Number density (at/b-cm)
^{16}O	3.6819×10^{21}	^{56}Fe	7.6647×10^{19}	^{242m}Am	1.3344×10^{17}
^{27}Al	4.7238×10^{22}	^{57}Fe	1.7390×10^{18}	^{243}Am	1.1821×10^{20}
^{40}Ca	7.3824×10^{19}	^{58}Fe	2.2744×10^{17}	^{242}Cm	3.7110×10^{16}
^{42}Ca	4.6928×10^{17}	^{238}Pu	1.8609×10^{18}	^{243}Cm	2.6073×10^{17}
^{43}Ca	9.5637×10^{16}	^{239}Pu	1.6575×10^{17}	^{244}Cm	3.6049×10^{20}
^{44}Ca	1.4443×10^{18}	^{240}Pu	3.5113×10^{19}	^{245}Cm	8.4356×10^{18}
^{46}Ca	2.6490×10^{15}	^{241}Pu	1.1230×10^{16}	^{246}Cm	1.1127×10^{21}
^{48}Ca	1.1868×10^{17}	^{242}Pu	4.6261×10^{17}	^{247}Cm	3.1377×10^{19}
^{54}Fe	5.0633×10^{18}	^{241}Am	3.2925×10^{19}	^{248}Cm	2.4653×10^{20}

Table 40: Theoretical yield limits of ^{252}Cf under different neutron fluxes.

Flux	(Y, C, A, D)	Flux	(Y, C, A, D)
1×10^{12}	(3.59×10^{-13}, 1.84×10^{-10}, 0.006, 200)	8×10^{14}	(2.33×10^{-5}, 1.20×10^{-2}, 82.837, 200)
5×10^{12}	(2.87×10^{-10}, 1.47×10^{-7}, 0.967, 160)	9×10^{14}	(3.91×10^{-5}, 2.01×10^{-2}, 87.579, 180)
1×10^{13}	(1.32×10^{-9}, 6.80×10^{-7}, 1.271, 200)	1×10^{15}	(3.42×10^{-5}, 1.76×10^{-2}, 88.393, 180)
2×10^{13}	(3.86×10^{-8}, 1.98×10^{-5}, 7.392, 200)	2×10^{15}	(6.96×10^{-5}, 3.57×10^{-2}, 90.123, 200)
3×10^{13}	(3.77×10^{-7}, 1.93×10^{-4}, 21.273, 120)	3×10^{15}	(6.16×10^{-5}, 3.16×10^{-2}, 89.171, 160)
4×10^{13}	(2.11×10^{-7}, 1.08×10^{-4}, 17.321, 200)	4×10^{15}	(6.50×10^{-5}, 3.34×10^{-2}, 91.729, 160)
5×10^{13}	(2.83×10^{-7}, 1.45×10^{-4}, 21.148, 160)	5×10^{15}	(7.27×10^{-5}, 3.73×10^{-2}, 91.696, 200)
6×10^{13}	(7.99×10^{-7}, 4.10×10^{-4}, 42.353, 160)	6×10^{15}	(6.77×10^{-5}, 3.47×10^{-2}, 92.503, 160)
7×10^{13}	(1.08×10^{-6}, 5.52×10^{-4}, 38.094, 160)	7×10^{15}	(8.22×10^{-5}, 4.22×10^{-2}, 92.581, 160)
8×10^{13}	(1.09×10^{-6}, 5.58×10^{-4}, 27.372, 200)	8×10^{15}	(8.10×10^{-5}, 4.16×10^{-2}, 93.566, 180)
9×10^{13}	(1.35×10^{-6}, 6.95×10^{-4}, 36.751, 200)	9×10^{15}	(1.00×10^{-4}, 5.15×10^{-2}, 96.229, 200)
1×10^{14}	(2.48×10^{-6}, 1.27×10^{-3}, 35.939, 180)	1×10^{16}	(1.07×10^{-4}, 5.49×10^{-2}, 96.801, 160)
2×10^{14}	(6.76×10^{-6}, 3.47×10^{-3}, 66.059, 200)	2×10^{16}	(7.99×10^{-5}, 4.10×10^{-2}, 95.878, 100)
3×10^{14}	(1.46×10^{-5}, 7.50×10^{-3}, 58.730, 180)	3×10^{16}	(1.01×10^{-4}, 5.18×10^{-2}, 95.945, 80)
4×10^{14}	(1.50×10^{-5}, 7.67×10^{-3}, 67.884, 180)	4×10^{16}	(1.11×10^{-4}, 5.72×10^{-2}, 99.247, 180)
5×10^{14}	(1.47×10^{-5}, 7.52×10^{-3}, 72.264, 200)	5×10^{16}	(8.54×10^{-5}, 4.38×10^{-2}, 97.888, 60)
6×10^{14}	(1.90×10^{-5}, 9.74×10^{-3}, 73.315, 200)	1×10^{17}	(1.36×10^{-4}, 6.98×10^{-2}, 99.181, 80)
7×10^{14}	(2.39×10^{-5}, 1.23×10^{-2}, 85.820, 200)		

irradiation is the main production method of medical isotopes, and the world is speeding up research reactor construction and medical isotopes production.

The reactor energy spectrum significantly affects the production efficiency of medical isotopes. Due to the difficulty of precisely regulating the reactor energy spectrum, the actual production efficiency of medical isotopes is currently far below the theoretical maximum production efficiency. However, we still do not know the theoretical maximum yield of various medical isotopes, so we do not know how large this gap is and how much potential is left for improving the production efficiency of medical isotopes.

We firstly determine the theoretical yield limits of 20 medical isotopes (^{14}C, ^{32}P, ^{47}Sc, ^{60}Co, ^{64}Cu, ^{67}Cu, ^{89}Sr, ^{90}Y, ^{99}Mo, ^{125}I, ^{131}I, ^{153}Sm, ^{161}Tb, ^{166}Ho, ^{177}Lu, ^{186}Re, ^{188}Re, ^{92}Ir, ^{225}Ac, ^{252}Cf) based on genetic algorithms and burnup algorithms. The theoretical maximum yield, transmutation rate of nuclides, nuclide abundance and required irradiation time of these medical isotopes at different flux levels are given for 8400 (20×35×12 combinations) scenarios.

These data show the transmutation limit of nuclides under the current irradiation conditions, quantify the gap between the current actual yield and the maximum yield, determine the potential for improving the current yield of medical isotopes, and help readers quickly estimate the yield and economy of a reactor for the medical isotopes production, and provide reference information for reactor construction and medical isotope production.

Data Availability

All data can be available through the Link: https://github.com/Panqingquan/Theoretical-Yield-Limits-of-In-reactor-Medical-Isotopes-Production.git

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

CRediT Statement

Qingquan Pan and **Yun Cai** contributes to the concept, calculation, analysis, and writing.

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