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Transmutation investigation of a typical VVER-1000 reactor burnup products to less toxicity isotopes in a fusion-fission hybrid reactor

Tipik VVER-1000 reaktör burnup ürünlerinin füzyon-fisyonlu hibrit reaktörde daha az toksisite izotoplarına dönüştürülmesinin incelenmesi

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Transmutation Investigation of a Typical VVER-1000 Reactor Burnup Products to less Toxicity Isotopes in a Fusion-Fission Hybrid Reactor

Highlights

- *Transmutation of burnup products of a VVER-1000 reactor in a fusion-fission hybrid reactor*
- *Burnup results using MCNPX 2.6.0 calculation code*
- *Decrement of mass and activity level of VVER wastes as IAEA waste level*

Graphical Abstract

The burnup products of a typical VVER-1000 were used as a hybrid reactor fuel and the activity and mass of wastes have been studied for the times of before and after burnup of a hybrid reactor and compared with the results of previous investigations.

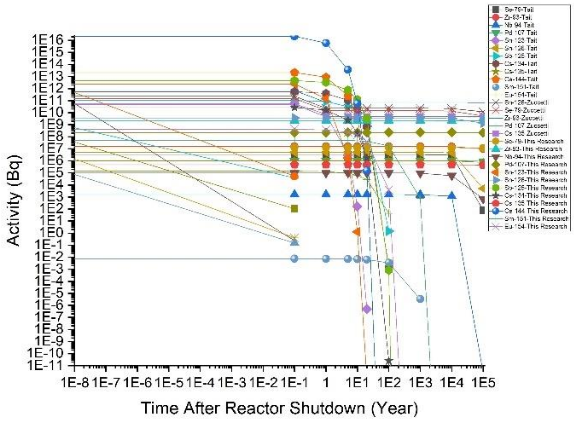

Figure. Activity of remaining waste isotopes after and before burnup of hybrid reactor comparing with previous investigation

Aim

Aim of the study was to show the capability of hybrid reactor in transmutation of a VVER waste.

Design & Methodology

The investigation was done numerically using MCNPX 2.6.0 calculation code. The reactor designs were based on VVER-1000 design and SABR reactor.

Originality

Investigation of VVER waste burning capability of a hybrid reactor.

Findings

Results have shown that VVER wastes were transmuted to less toxicity elements in terms of mass and activity level according to IAEA waste level and comparing to the results of the related researches.

Conclusion

The results proved the waste transmuting capability of a hybrid reactor.

Declaration of Ethical Standard

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Transmutation Investigation of a Typical VVER-1000 Reactor Burnup Products to less Toxicity Isotopes in a Fusion-Fission Hybrid Reactor

Araştırma Makalesi / Research Article

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ABSTRACT

Transmutation of burnup products for a typical VVER-1000 reactor in a fusion-fission hybrid reactor has been investigated using MCNPX 2.6.0 calculation code. Burnup calculation of a fission reactor was performed for a 1000 MW practical power of a VVER reactor core using UO2 fuel and light water as its coolant and moderator, as well. The burnup products have been classified and separated according to their half-lives and their usages, and the remaining wastes were used as fuels for a fusion-fission hybrid reactor. The burnup calculation was also implemented for the fission wastes of the mentioned hybrid reactor, and the remaining products were separated and classified. The results showed that fission products can be transmuted into useful elements or to elements with less toxicity (with the decrement of activity) and less mass, and according to the IAEA toxicity limit of nuclear wastes, the levels of radioactivity and toxicity decreased. The results confirmed appropriately "the waste transmutation capability" of a fusion-fission hybrid reactor.

Keywords: VVER-1000 reactor, fusion-fission hybrid reactor, MCNPX 2.6.0 calculation code, waste transmutation.

Tipik VVER-1000 Reaktör Burnup Ürünlerinin Füzyon-Fisyonlu Hibrit Reaktörde Daha Az Toksisite İzotoplarına Dönüştürülmesinin İncelenmesi

ÖZ

Bir füzyon-fisyon hibrid reaktöründe tipik bir VVER-1000 reaktör için yanma ürünlerinin nakli MCNPX 2.6.0 hesaplama kodu kullanılarak araştırılmıştır. Bir fisyon reaktörünün yanma hesaplaması, soğutucu ve ayrıca moderatör olarak UO2 yakıt ve hafif su kullanılarak VVER reaktör çekirdeğinin 1000 MW pratik gücü altında yapıldı. Yanan ürünler yarılanma ömürlerine ve kullanımlarına göre sınıflandırılmış ve ayrılmıştır ve geri kalan atıklar bir füzyon-fisyon hibrit reaktöründe yakıt olarak kullanılmıştır. Yanma hesaplaması hibrid reaktördeki fisyon atıkları için de uygulanmış ve geri kalan ürünler ayrılmış ve sınıflandırılmıştır. Sonuçlar, fisyon ürünlerinin yararlı elementlere veya aktivite azalması ve ayrıca kütle ile daha az toksisite elementlerine aktarıldığını ve nükleer atıkların IAEA toksisite sınırına göre radyoaktivite ve toksisite seviyesinin azaldığını gösterdi. Sonuçlar, bir füzyon-fisyon hibrit reaktörünün "atık dönüşüm kabiliyetini" uygun şekilde teyit etti.

Anahtar Kelimeler: VVER-1000 reaktör, füzyon-fisyon hibrit reactor, MCNPX 2.6.0 hesaplama kodu, atık dönüşümü.

1. INTRODUCTION

The most important restriction to the widespread usage of a nuclear power plant is probably the challenge related to its intense radioactive nuclear wastes. Therefore, the transmutation of nuclear wastes has become an international hotspot issue [1, 2].

Using a high-energy neutron spectrum, the nuclear wastes can be transmuted to light elements (isotopes) with much shorter half-lives [3].

Transmutation of long-lived Actinides is one of the most attractive capabilities of a fast neutron and is being investigated in many studies for different types of reactors. For example, Iwasaki et al., investigated the effects of thermal and fast neutrons on transmutation of TRUs [4] and Wiese and coworkers investigated it for transmutation of Actinides [5]. Also, Martinez and coworkers investigated the transmutation of nuclear wastes, using fast neutrons of an ADSR reactor [6].

Among these suggested types, the most attractive one is the concept of the fusion-fission hybrid reactor.

The Fusion–Fission Hybrid Reactor (FFHR) is a fusion neutron source surrounded by a fission blanket. The "Fusion–Fission hybrid reactor can be the first milestone of fusion technology and achievable in near future", as Zu said [7].

The researches are focused on the subcriticality of the hybrid reactors because of two important advantages: maintenance of neutron chain reaction at the same power

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as neutron flux increases, and also an increased reactivity safety margin to a prompt critical power excursion [8].

The design performance of a hybrid reactor is also an interesting field of research. Different hybrid designs were suggested, and their different performances were analyzed and studied. For example Subcritical Advanced Burner Reactor (SABR) [9], dual-cooled waste transmutation blanket (DWTB) [10], Fusion Transmutation of Waste Reactor (FTWR) [11] are proposed for magnetic confinement fusion (MCF) [12], and Laser Inertial Fusion Energy (LIFE) [13] is suggested for inertial confinement fusion (ICF) [14].

The waste transmutation capability of the hybrid reactors is also much higher rather than that of Accelerator Driven Subcritical Reactors (ADSR) [15].

The investigations related to the mentioned capability of hybrid reactors are mostly focused on transuranic elements [16]. Wolkenhauer et al.'s research [17], focusing on the transmutation of high-level radioactive waste, is of the first ones in this filed. They reported the transmutation parameters of four radioactive elements, Sr-90, Cs-137, Kr-85 and I-129, and the transmutation of Actinides using different D-T or D-D plasma. The results showed a visible decrement in the toxicity parameters.

After Wolkenhauer's study, some other studies were published. For example, Bethe published his research in the journal of PHYSICS TODAY [18]; however, he mostly focused on the power generation and combination of fusion and fission in order to have a positive gain and to convert the fertile fuels to the fissile ones, and the fission of fertile fuels, as well. Feng published his study in 1995, which was in the context of transmutation of Np-237 in a hybrid reactor [19] and the other one for other transuranic isotopes in 2003 [20].

But since the transuranic elements are mostly fertile or fissile fuels [21], it is more attractive to investigate the transmutation of the elements with lower atomic numbers that have no medical, industrial, or fueling usages, such as Cs-135 or Se-79.

In this work, the burnup calculation for a typical VVER reactor has been performed and then analyzed, at first. Then, the same calculation was performed using the Monte-Carlo MCNPX code, as described in the next section. The waste products were classified according to their usages and were separated according to their half-lives. The isotopes with shorter half-lives were separated and only medium or long-lived products were used for hybrid fuels, as will be described in section 3. In section 4, the selected wastes were used as fuels in the hybrid core, and the remaining products were calculated. The hybrid reactor design selection in this study is based on recent research of Prof. Stacey et al. in the Georgia Technology Institute [22], and appropriate changes in material and geometry have been considered, as well for this design. Finally, the activity and the mass of the remaining products were compared with activities and masses of LWR waste products of the IAEA Waste Limit Standards in 5.1 and 5.2 sections, and then in section 5.3, the results were compared with the results of some other studies in order to validate and to analyze them.

2. MATERIAL and METHOD

As mentioned before, it is more attractive to investigate the transmutation of the elements with lower atomic numbers that have no usage as medicine, industrial material, or fuel. In 2003, Di-pace and Natalizio published a paper [23], focusing on radiotoxicity index of isotopes Tc-99, I-129, Sn-126, Se-79, Zr-93, Cs-135, Ca-41, Pd-107 fission products and U-238 and Pu-239 for six different models of fusion reactor. In 2018, Zucchetti et al. [24] examined the total radiotoxicity of PWRs and 6 different models of fusion reactors based on Di pace's work.

The fission products should be calculated and examined in order to be used in hybrid reactors as fuels. Tait et al. [25] have investigated the output rates of the fuel elements of a CANDU reactor for their activities and masses at different time intervals after the reactor shutdown.

In this work, the simulation of a VVER and a hybrid reactor were performed using the Monte-Carlo calculation code (MCNPX 2.6.0) [26]. The geometry and the materials of the simulations were applied using the safety report of reactors, and appropriate "Cards" were implemented as variables for the studied system. The card "BURN" was used as a burnup rate and the cards "TIME" and "PFRAC" were selected for the power distribution rate of the VVER-1000 core, illustrated in Figure 1 [27].

According to Figure 1, about three hours after the beginning of the process, the reactor power decreases to half of its initial power and then increases to full power again, which lasts some hours. The "TIME" card is filled

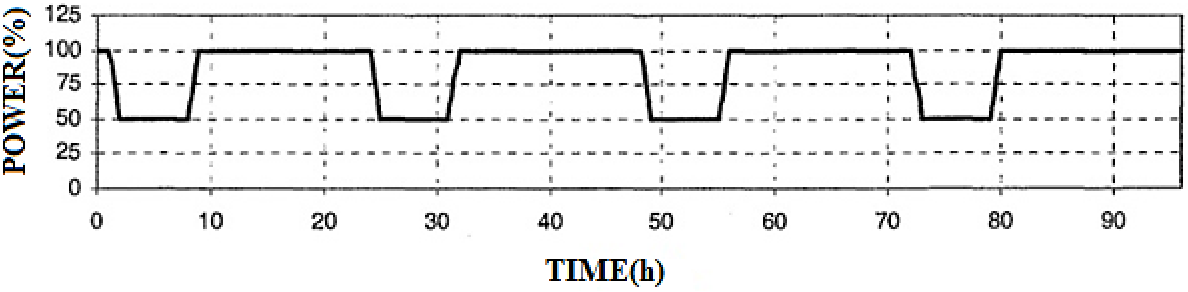

Figure 1. Power distribution rate of VVER-1000 core [27].

as the time interval, in which the reactor works with a specific power and “PFRAC” will be the power of each time interval as shown in Figure 1.

3. NUCLEAR WASTE PRODUCTION OF THE VVER-1000

For the waste production calculation of a VVER reactor, a typical VVER-1000 core was simulated first and the burnup rate was calculated for it. The geometrical parameters and the materials used in the reactor are reported in Table 1, and the fuel assemblies were put in the core as shown in Figure 2.

3.1. VVER-1000 Core Simulation

The main parameters of the fission reactor, taken from a typical VVER-1000 safety report, are listed in Table 1, and the main core of the VVER-1000 reactor is shown with fuel assemblies and different enrichment levels defined by different colors in Figure 2.

Table 1. The Main Parameters of the VVER-1000 Reactor [27].

Variable	**Value**
Fuel	UO_2 pellets
Cladding material	alloy Zr+1% Nb
Absorbing material	B_4C+(Dy_2O_3 TiO_2)
Zr + 1 %Nb density, kg/m^3	6.55
Fuel density (UO_2), kg/m^3	(10.4 ... 10.7} 10^3
Absorbing material density, kg/m^3, not less than - Boron Carbide (kg/$m^{3)}$ - Dysprosium Titanate (kg/$m^{3)}$	 1.7*10^3 4.9*10^3
Number of FAs in the core, pcs	163
Number of control rod drives, pcs	to 121
Number of CPS AR, pcs - For the first fuel charge - Starting from the second fuel charge	 85 103
Number of FAs with BAR bundle, pcs - for the first fuel charge - for the stationary fuel charge	 42 18
The number of fuel rods in the FA, pcs.	311
Number of absorbing elements in CPS AR, pcs	18
Enrichment percentage, %	
Conventional mass fraction of Uranium-235, %, not more than	1.60,2.40,3.30,3.70,4.10
Conventional mass fraction of Uranium-236, %, not more than	0.1
Mass fraction of mixture of Uranium isotopes, %, not more than	87.9
Mass fraction of Uranium isotope mixture in fuel, %, not less than	87.8
Core equivalent diameter, m	3.16
The pitch between the assemblies, m	0,236
The pitch between the fuel rods, m	12.75*10^{-3}
Height of the heated part (in the cold state), m	3.53
FA height, m	4.57
FA pitch, cm	23,6
Nominal CPS AR height, m	4,215
Nominal diameter of absorbing element cladding, m	8.2*10^{-3}
Nominal thickness of absorbing element cladding, m	0.5*10^{-3}
The diameter of the vessel cylindrical part in the core area, m	4.535
Nominal height of absorbing material stack, m Boron Carbide Dysprosium Titanate Total	 3.2 0.3 3.5
Spacing grid: Number, pcs. Material	 15 alloy Zr+1% Nb
Guide channel: Number, pcs Material Outer diameter, m Inside diameter, m	 18 alloy Zr + 1 % Nb 13.0*10^{-3} 11.0*10^{-3}
Central tube: Number, pcs Material Outer diameter, m Inside diameter, m	 1 alloy Zr + 1 % Nb 13.0*10^{-3} 11.0*10^{-3}
Tube for ICID: Number, pcs Material Outer diameter, m Inside diameter, m	 1 alloy Zr + 1 % Nb 13.0*10^{-3} 11.0*10^{-3}

The fuel assembly arrangement of the LWR core is as shown in Figure 2. The ^{235}U enrichments, used in the fuel assemblies, are 1.6, 2.4 and 3.6 fissile fuel percent. A burnable poison was added to some of the fuel rods that had an enrichment level of 2.4 and 3.6 percent of the fissile fuel.

Water holes with different sizes are located around the fuel assemblies in the core barrel, and the core baffle, pressure vessel and the coolant are located around the core, which in between, the coolant flows.

Assemblies with violet, purple and brown colors don’t have burnable poisons, while the blue, green and red assemblies are the ones with burnable poisons.

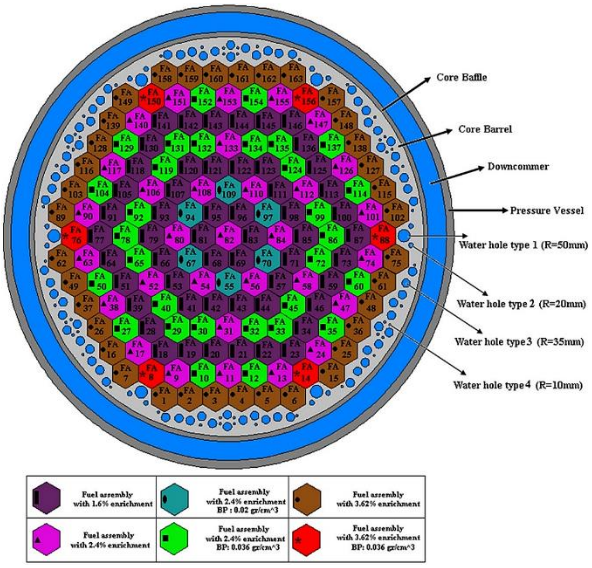

Figure 2. The VVER-1000 core and fuel assemblies with different enrichment levels [29].

3.2. Fission Reactor Burnup

The rates of the burnup products for the VVER core were calculated and separated regarding their medical or industrial usages, while the remaining long-lived wastes were used as fuels for the hybrid reactor. The result of the burnup calculation is in an appropriate adaptation to a typical VVER-1000 safety report contents [27]. The waste radio-nuclides of the fission reactor burnup, their masses, activities, and half-lives of isotopes are listed in Table 2.

As previously stated, The waste products were classified according to their usages and were separated according to their half-life durations, so that the transuranic elements and some useful isotopes like Tc-99 or Ca-41 and I-129 were separated and were not taken into account to be used as fuels for the hybrid reactor.

Table 2. Burnup products of a typical VVER-1000 using MCNP code.

Isotope	Mass (g)	Activity (Bq)	Sp. Act. (Bq/g)	Half-life (years)
Se-79	2.48E-03	1.26E+07	5.07E+09	1.13E+6
Zr-93	2.36E+01	2.19E+09	9.32E+07	1.53E+6
Nb-94	1.41E-05	9.77E+04	6.96E+09	2.03E+4
Pd-107	1.19E+01	2.27E+08	1.91E+07	6.5E+6
Sn-123	7.89E-03	2.40E+12	3.04E+14	0.354
Sn-126	3.51E+00	3.69E+09	1.05E+09	1E+5
Sb-125	1.20E-01	4.66E+12	3.89E+13	2.7582
Cs-134	5.55E-04	2.66E+10	4.81E+13	2.0648
Cs-135	1.13E-02	4.81E+05	4.26E+07	2.3E+6
Ce-144	1.84E+02	2.16E+16	1.18E+14	0.78
Sm-151	5.39E-05	5.25E+07	9.73E+11	90
Eu-154	4.26E-05	4.26E+08	9.99E+12	8.593

4. WASTE TRANSMUTATION IN A HYBRID REACTOR

The waste isotopes (some of the burnup products) have been used as fuels for a hybrid reactor in order to transmute the waste nuclides. The geometric parameters were shown in Figure 3 and the main parameters of the core and shields are given in Tables 3 and 4.

4.1. Hybrid Core Simulation

The hybrid core simulation was performed like the parameters in the study of Prof. Stacey et al. in the Georgia Technology Institute [22] he core geometry and dimensions are shown in Figure 3, and the main parameters of the reactor burnup are listed in Tables 3 and 4.

The burnup calculation was performed using the MCNPX calculation code, using "BURN" and some other related cards. The reactor parameters and materials were used as shown in Figure 3 and Tables 3 and 4.

Table 3. Materials and Some Other Dimensions of the studied reactor [22].

Parameters	Values
Materials—fuel/ Tritium breeder/ Clad and structure	ThO2/ Li2O/ ODS MA957
Shield Materials	Graphite, Tungsten Carbide, Boron Carbide, Na
Divertor Materials	Tungsten, CuCrZr, Na cooled
First wall Materials	Be, CuCrZr, ODS steel
Materials— Reflector assembly in-core (Vol %)	ODS Steel (58.1%), SiC (6.6%), Na (35.3%)
Materials— Graphite reflectors (Vol %)	Graphite (90%), Na (10%)
Fuel/Clad/Bond/Insulator/Duct/Coolant/Wire (Vol %)	22.3/17.6/7.4/6.5/9.3/35.3/1.5%
Number of fuel assemblies/Fuel rods/ Modular pools	800/469 per assembly, 375200 total/10
Height—fusion core/pin/duct/assembly	65.0/204.415/215.135/274.901 cm
Thickness—first walls	8.1 cm (1 cm Be, 2.2 cm CuCrZr, 4.9 cm ODS steel)
Thickness—Cladding/Duct/Pin/Fuel	0.0559/0.394/0.539/ 0.370 cm
Pitch—pin/ assembly	0.6346/16.142 cm

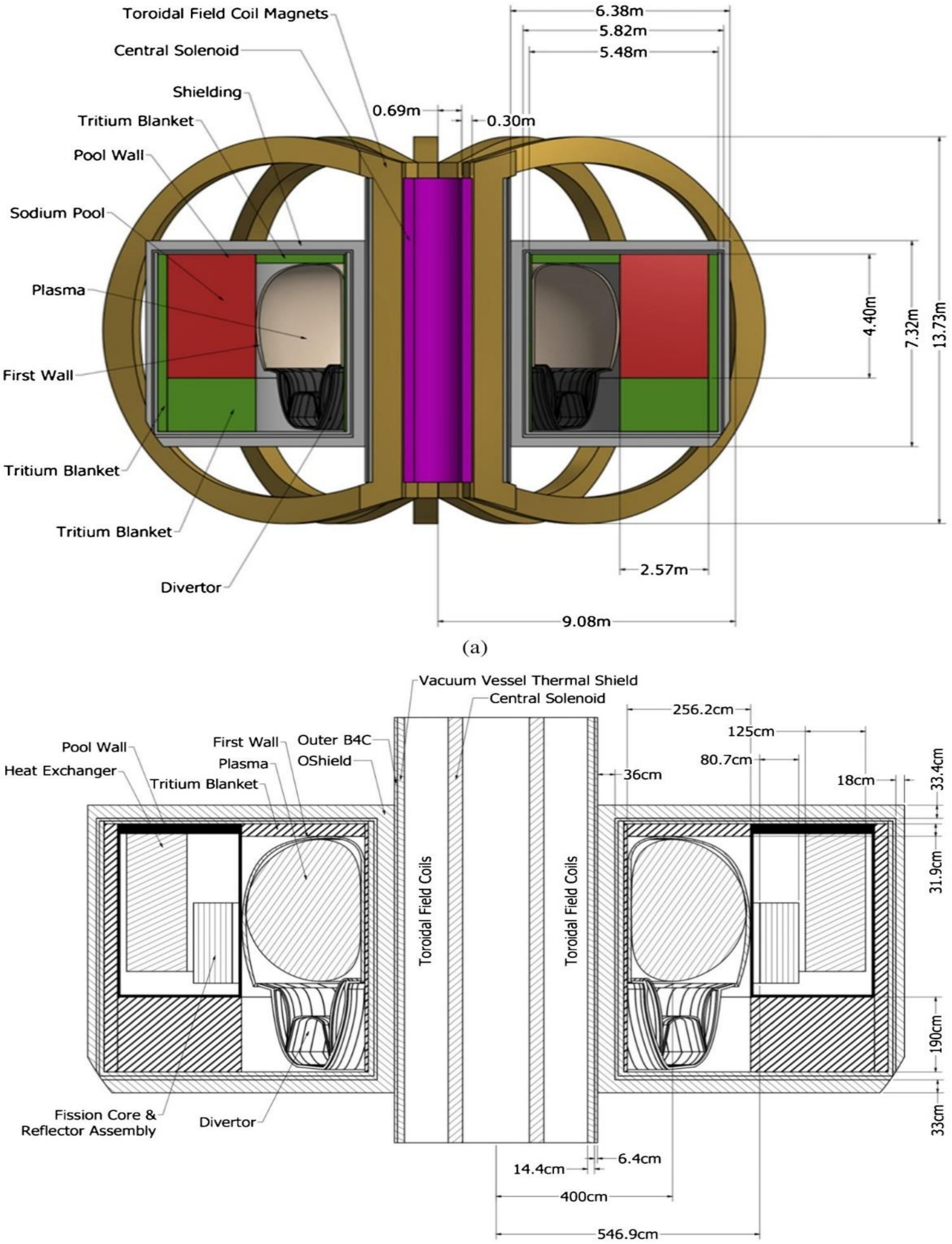

Figure 3. (a) Perspective view of a SABR configuration; (b) Radial view of a SABR configuration [22].

Table 4. Materials and Thicknesses of the Shields [22].

Name	**Materials**	**Thickness (cm)**
Ins (Organic insulator)	The effective layer of glass-filled polyimide	4.42
TF case	SS316LN-IG (stainless steel)	
	Outer side	7.08
	The inner side (next to plasma)	20.48
VV (Vacuum Vessel)	50 vol % ODS steel, 50 vol % He	14.35
Graphite	Graphite with 10 vol % Na	7
FW (first wall) part 1	Beryllium	1
FW part 2	A mix of ODS steel, Na, and CuCrZr	2.2
FW part 3	80 vol % ODS steel, 20 vol % Na	4.9
OB$_4$C	B$_4$C with 5 vol % Na	6.35
OShield-1	WC (Tungsten carbide) with 5 vol % Na	36
OShield-2	WC with 5 vol % Na	32.4
OShield-3	WC with 5 vol % Na	18
OShield-4	WC with 5 vol % Na	33
IB4C-1	B$_4$C with 10 vol % Na	6.5
IB4C-2	B$_4$C with 10 vol % Na	7
IB4C-3	B$_4$C with 10 vol % Na	6
IB4C-4	B$_4$C with 10 vol % Na	10
IShield-1	WC with 10 vol % Na	12
IShield-2	WC with 10 vol % Na	n/a
IShield-3	WC with 10 vol % Na	10
IShield-4	WC with 10 vol % Na	10
Trit-1 (Tritium Breeding)	Li$_2$O	6.7
Trit-2	Li$_2$O	31.9
Trit-3	Li$_2$O	The volume under the pool except divertor part
Trit-4	Li$_2$O	28

Ins: Insulator, SS: Stainless Steel, VV: Vacuum Vessel, FW: First Wall, WC: Tungsten Carbide, OB$_4$C: Outer Boron Carbide, OShield: Outer Shield, IShield: Inner Shield, Trit: Tritium Breeding.

4.2. Hybrid Waste Burnup Calculation

The results were classified and separated regarding that either they have usages or being the wastes, and the remaining wastes were listed in Table 5 regarding their masses, activities and half-lives. Six radionuclides, Se-79, Zr-93, Pd-107, Sn-126, Sb-125 and Cs-135 remained after the burnup of the fuel in the hybrid reactor.

Table 5. Burnup product of hybrid reactor

Isotope	**Mass (g)**	**Activity (Bq)**	**Sp. Act (Bq/g)**	**Half-Life(y)**
Se-79	8.13E-11	4.14E-01	5.07E+09	1.13e6
Zr-93	4.10E-04	3.81E+04	9.32E+07	1.53e6
Pd-107	1.24E-08	2.35E-01	1.91E+07	6.5e6
Sn-126	1.01E-07	1.05E+02	1.05E+09	1.0e5
Sb-125	1.35E-09	5.25E+04	3.89E+13	2.7582
Cs-135	3.52E-09	1.50E-01	4.26E+07	2.3e6

5. WASTES LEVELS AND ACTIVITY LIMITS

Table 6 shows the different ranges of activities and half-lives of different wastes (wastes levels) described in the IAEA safety report [28]. According to the contents of Table 6 and the results in Table 5, only Sb-125 has the half-life less than 15 years, while the half-lives of the other five isotopes are in the range of higher than 30 years.

Table 6. Half-life and activity range for different wastes [28].

Waste Level	**Half-life**	**Activity**	**Volume**	**Example**
i	<100 d	100 MBq	Small	Y-90, Au-198 (Brachytherapy)
ii	<100 d	5 TBq	Small	Ir-192 (Brachytherapy)
iii	<15 a	<10 MBq	Small	Co-60, H-3 (Tritium targets), Kr-85
iv	<15 a	<100 TBq	Small	Co-60 (irradiators)
v	<30 a	<1 MBq	Small	Cs-137 (Brachytherapy, moisture density detectors)
vi	<30 a	<1 PBq	Small	Cs-137 (irradiators) Sr-90 (thickness gauges, radioisotope thermoelectric generators (RTGs))
vii	>30 a	<40 MBq	Small, but may be large numbers of sources (up to tens of thousands) Activity	Pu, Am, Ra (static eliminators)
viii	>30 a	<10 GBq		Am-241, Ra-226 (gauges)

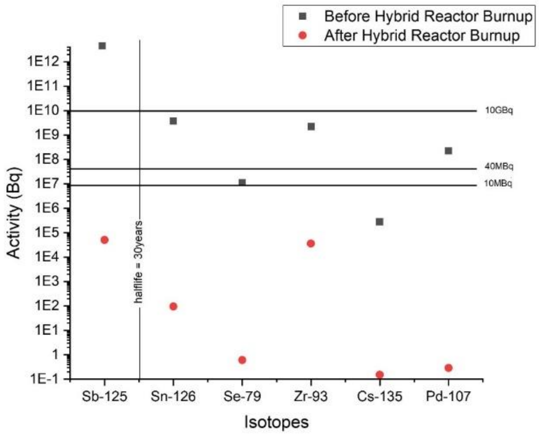

Figure 4. Activity of remaining waste isotopes after and before the burnup of hybrid reactor

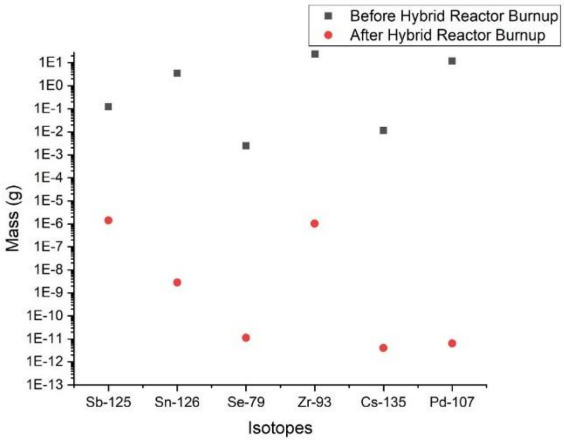

Figure 5. Masses of remaining wastes isotopes after and before hybrid reactor burnup.

The activity of the Waste

The activity of the burnup products of the hybrid reactor is shown in Figure 4. The squares show the activity of elements before burnup and the circles show the activity of elements after the burnup. The elements are listed based on increasing half-lives.

- Before the Hybrid Reactor Burnup

The results before the burnup show that Sb-125 has the most activity and also the least half-life, as shown in IAEA waste levels in the row “vi” of Table 5. According to activity, Sn-126, Zr-93, and Pd-107 have the most activities after Sb-125, putting them in the row “viii”, and Se-79 and Cs-135 will be considered in the waste level of “vii”.

- After the Hybrid Reactor Burnup

The activity of all of the elements after the burnup in the hybrid reactor was decreased. The most activities between elements after the hybrid reactor burnup are for Sb-125 and also Zr-93. The activity level of Sb-125 changes from level “vi” to level “iii”, and the activity level of all other elements changed to “vii”.

5.1. Mass of Burnup Products In Hybrid Reactor Burnup

The masses of waste elements before and after the burnup, illustrated in Figure 5, confirm the waste burning capability in the hybrid reactor. The squares and circles in Figure 5 demonstrate the mass of isotopes before and after burnup. The results indicate that all of the isotopes show decreases in their masses.

5.2. Benchmark and validation

The obtained results were compared with similar results in order to validate the results of this study. The results have been compared with the result of Tait et al.’s work, which studied the radioactivity and mass of CANDU fuels, and Zucchetti, which studied the total radio-toxicity of PWR and 6 different models of fusion reactors based on Di-pace’s study. The activity of isotopes has been added in Figure 6, and their masses were added to Figure 7.

Also, the mass and radioactivity of isotopes before and after the hybrid reactor burnup have been added to the Figures 6 and 7 in order to compare the activities and masses of the studied isotopes in the time interval between the time they are naturally radioactive and the time they are irradiated by 14.1 MeV neutrons spreading from fusion chamber of the hybrid reactor.

The results may be affected by various parameters of the reactor, such as fissile fuel enrichment, reactor design and geometry, the materials used in the reactor, and the percentage of each element, the source, the irradiated particles, the source energy, and so on. Therefore, the results may be different, but the changing procedure indicates the correct way to have a good vision of the accuracy of the results.

The results show a good adaptation between the our obtained results and results of Tait et al.’s and Zucchetti et al’s works. Considering the figures 6 and 7, the change procedures of radioactivity and mass of specific isotopes are the same. The amount of radioactivity and mass of remaining wastes may differ in amount according to various parameters such as fissile fuel enrichment, reactor design and geometry or the materials used in the reactor but the same change procedure indicates that the results are of a high degree of accuracy and precision.

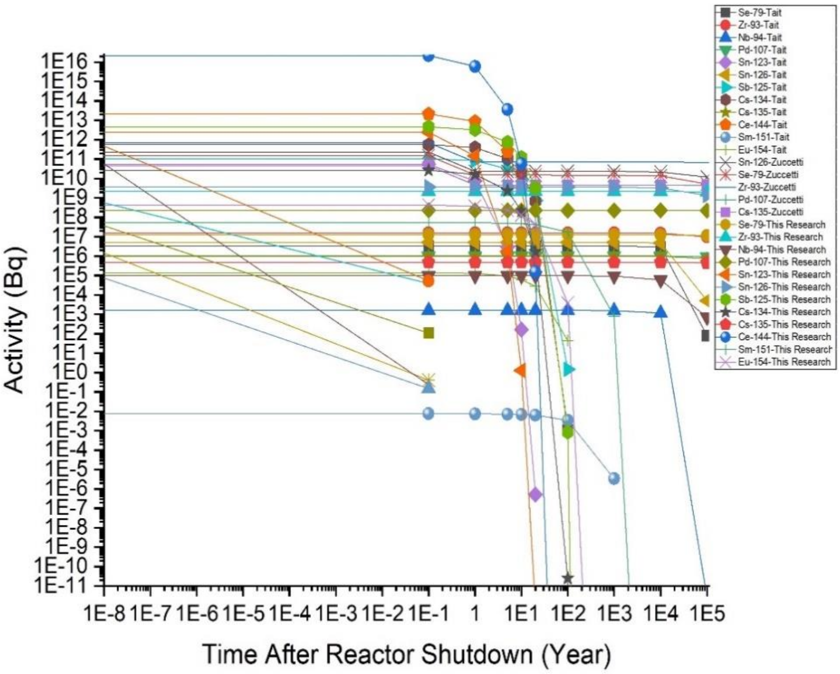

Figure 6. activity of fission products before and after hybrid reactor, and comparing the results with

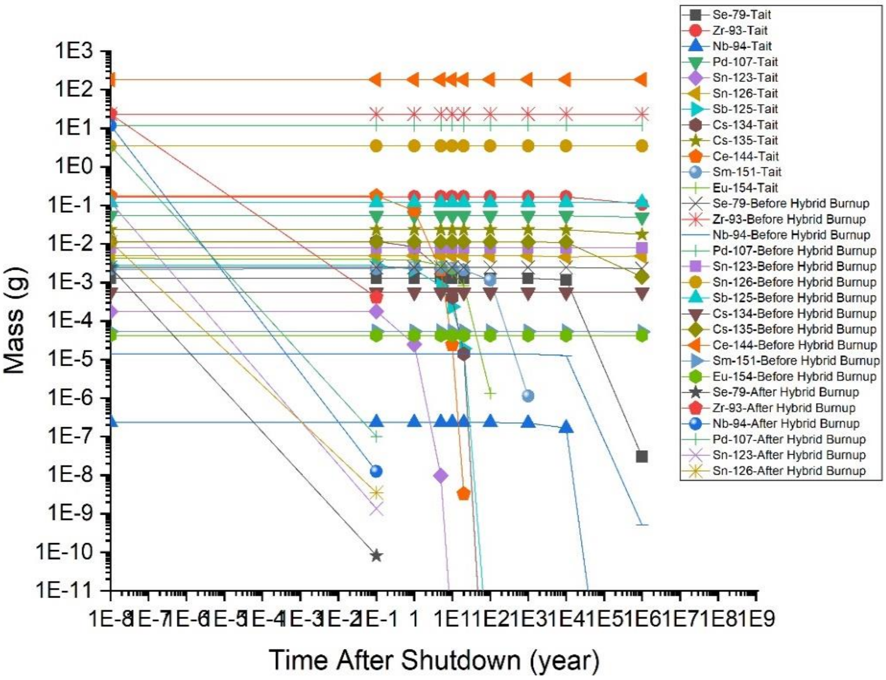

Figure 7. Masses of fission products before and after the hybrid reactor; and comparing the results

Another key point of the Figures 6 and 7 is the fast rate of waste annihilation in a FFHR, which is concluded from a high decrement in the activities and masses of the wastes in only 0.1 year, and for the isotopes with a half-life of 10^6 years order, this is actually interpreted as annihilation.

6. CONCLUSION

The main important result of this study is the nuclear burning capability of wastes. The produced waste elements from the VVER-1000 core burnup were calculated and classified based on their industrial or medical usages, and the remaining wastes were used as fuels for a fusion-fission hybrid reactor. Six isotopes (Se-79, Zr-93, Pd-107, Sn-126, Sb-125 and Cs-135) were selected as fuels for hybrid burnup.

The burnup of the hybrid reactor was simulated and the activity and mass of the elements were calculated. Both quantities (activity and mass) of the remaining wastes showed a decrease, and the waste levels of Zr-93, Pd-107, Sn-126 and Sb-125 changed according to the IAEA waste limits.

The accuracy of the results of the activity and mass have been examined using some other studies and the results showed a good adaptation between them, indicating

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DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS’ CONTRIBUTIONS

Seyyed Mahdi Teymoori Sendesi: Performed the material identification and adjustment, data collection and analysis and write the first draft of the manuscript

Prof. Dr. Abbas Ghasemizad: Reviewed and commented on previous versions of the manuscript.

All authors read and approved the final manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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