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

Yazar(lar) (Author(s)): Seyyed Mahdi TEYMOORI SENDESI¹, Abbas GHASEMIZAD²

ORCID¹: 0000-0002-8871-7879
ORCID²: 0000-0001-6452-6309

Bu makaleye şu şekilde atıfta bulunabilirsiniz (To cite to this article): Teymoori Sendesi S. M., Ghasemizad A., “Transmutation investigation of a typical VVER-1000 reactor burnup products to less toxicity isotopes in a fusion-fission hybrid reactor”, Politeknik Dergisi, (“*”): *, (*).

Erişim linki (To link to this article): http://dergipark.org.tr/politeknik/archive

DOI: 10.2339/politeknik.766184
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

Seyyed Mahdi TEYMOORI SENDESI, Abbas GHASEMIZAD*
Deopartmento Physics, University of Guilan, İran
(Geliş/Received : 08.07.2020 ; Kabul/Accepted : 08.09.2020)

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.

1. INTRODUCTION

The most important restriction to the widespread usage of a nuclear power plant is probably the challenge related to the 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.

*Sorumlu yazar (Corresponding Author)
e-posta : ghasemi@guilan.ac.ir
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, Be the 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 usage as medicine, industrial material, or fuel. In 2003, Di-pace and Natalizio published a paper [23], focusing on radiotoxicity index of isotopes Te-99, F-19, Sr-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].](image-url)
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     | UO₂ pellets |
| Cladding material | alloy Zr+1% Nb |
| Absorbing material | B₄C+(Dy₂O₃)TiO₂ |
| Zr + 1%Nb density, kg/m³ | 6.55 |
| Fuel density (UO₂), kg/m³ | (10.4 ... 10.7) 10³ |
| Absorbing material density, kg/m³, not less than | 1.7*10³ |
| - Boron Carbide (kg/m³) | 4.9*10³ |
| - Dysprosium Titanate (kg/m³) |
| Number of FAs in the core, pcs | 163 |
| Number of control rod drives, pcs | 121 |
| Number of CPS AR, pcs - For the first fuel charge | 105 |
| - Starting from the second fuel charge | 105 |
| Number of FAs with BAR bundle, pcs - for the first fuel charge | 42 |
| - for the stationary fuel charge | 18 |
| The number of fuel rods in the FA, pcs | 311 |
| Number of absorbing elements in CPS AR, pcs | 18 |
| Enrichment percentage, % | 1.6, 2.4, 3.3, 3.7, 0.4, 10 |
| Conventional mass fraction of Uranium-235, %, not more than | 1.6, 2.4, 3.3, 3.7, 0.4, 10 |
| Conventional mass fraction of Uranium-236, %, not more than | 0.1 |

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.

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 Te-99 or Ca-41 and I-129 were separated and were not taken into account to be used as fuels for the hybrid reactor.

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] the 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                  | ThO2/ Li2O/ ODS ODS MA957       |
| Clay Materials                          | ThO2/ Li2O/ ODS 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    | 65.0/204.415/215.1/35/274.901 cm |
| Thickness—first walls                   | 8.1 cm (1 cm Be, 2.2 cm CuCrZr, 4.9 cm ODS steel) |
| Thickness—Cladding/Duct/Pin/Fuel        | 0.059/0.394/0.539/0.370 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, Inner side: 20.48 |
| VV (Vacuum Vessel) | 50 vol % ODS steel, 50 vol % He    | 14.35 |
| Graphite           | Graphite with 10 vol % Na          | 7             |
| FW 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           |
| OBt               | Bt, 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            | Bt, C with 10 vol % Na             | 6.5           |
| IB4C-2            | Bt, C with 10 vol % Na             | 7             |
| IB4C-3            | Bt, C with 10 vol % Na             | 6             |
| IB4C-4            | Bt, 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) | Li2O                  | 65            |
| Trit-2            | Li2O                              | 31            |
| Trit-3            | Li2O                              | The volume under the pool except the interior part |
| Trit-4            | Li2O                              | 58            |

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       |

4.2. Hybrid Waste Burnup Calculation

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.

The remaining burnup products of the hybrid reactor were compared to the VVER burnup products regarding their activities and masses and according to the IAEA activity standards in Table 6, which were shown in Figure 4 and Figure 5.

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          | <10 d     | 57 Bq    | Small  | Ir-192 (Brachytherapy) |
| iii         | <15 a     | <10 MBq  | Small  | Co-60, H-3 (Tritium targets, Kr-85) |
| iv          | <15 a     | <100 TBq | Small  | Cs-137 (irradiators) |
| v           | <60 d     | <1 MBq   | Small  | Cs-137 (Brachytherapy, moisture detectors) |
| vi          | <30 a     | <1 PBq   | Small  | Cs-137 (irradiators) Sr-90 (thickness gauges, radiisotope thermoelectric generators (RTGs)) |
| vii         | >30 a     | <40 MBq  | Small  | Pu, Am, Ra (static eliminators) |
| viii        | >30 a     | <10 GBq  | Activity | Am-241, Ra-226 (gauges) |
5.1. 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 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 “vii”, 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”.

5.2. 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.

5.3. 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 10^7 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.

Acknowledgement

The authors wish to express their gratitude for the financial support provided by the University of Guilan for this work.

REFERENCES

[1] Yang C., Cao L., Wu H., Zheng Y., Xu T., "Neutronics analysis of minor actinides transmutation in a fusion-driven subcritical system", Fusion Engineering and Design, 88:277–283 (2013).
[2] Salvadori M., Palmieri G., "Radioactive waste partitioning and transmutation within advanced fuel cycles: Achievements and challenges", Progress in Particle and Nuclear Physics, 66:144–166, (2011).
[3] Greenspan L., "Fusion reactors blanket nucleonics", Progress in Nuclear Energy, 17:53–139 (1986).
[4] Iwamoto T., Hirakawa N. "Neutron economy of transmutation of TRU in thermal and fast neutron fields", Journal of Nuclear Science and Technology, 31:1255–1264 (1994).
[5] Wiese HW., "Actinide transmutation properties of thermal and fast fusion reactors including multiple recycling", Journal of Alloys and Compounds, 271–273:522–529, (1998).
[6] Herrera-Martinez A., Kadi Y., Parks G., Dahlfors M., "Transmutation of nuclear waste in accelerator-driven systems: Fast spectrum", Annals of Nuclear Energy, 34:564–578 , (2007).
[7] Zu T., Wu H., Zheng Y., Cao L., "Economics analysis of fuel cycle cost of fusion-fission hybrid reactors based on different fuel cycle strategies", Fusion Engineering and Design, 90:119–126, (2015).
[8] Bopp AT., Stacey WM., "Dynamic safety analysis of a subcritical advanced burner reactor", Nuclear Technology, 200:250–268, (2017).
[9] Stacey WM., Van Rooijen W., Bates T., Colvin E., Dion J., Feener J., Gayton E., Gibb D., Grennor C., Head J., Myers C., Schmitz A., Sommer C., Summer T., Teschea L., "A TRU-Zr metal-fuel-sodium-cooled fast subcritical advanced burner reactor", Nuclear Technology, 162:53–79, (2008).
[10] Wu Y., Zheng S., Zhu X., Wang W., Wang H., Liu S., Bai Y., Chen H., Hu L., Cheng M., Huango C., Huang D., Zhang S., Li J., Shi D., Huang Y., "Conceptual design of the fusion-driven subcritical system FDS-I", Fusion Engineering and Design, 81:1305–1311, (2006).
[11] Stacey WM., Manriquez J., Hoffmann EA., Kessler GP., Kirby CM., Maier AN., Noble JJ., Stopp DM., Ulreich DS., "A Russian transmutation of waste reactor", Fusion Engineering and Design, 63:81–86, (2002).
[12] D. Thomas J., "Magnetic Fusion Technology", Vol. 19, Springer-Verlag London, (2013).
[13] Wexler WR., Abbott R., Beach R., Blink J., Caird J., Brandt A., Farmer J., Halsey W., Ladrán T., Latkowski J., Macintyre A., Miles R., Storm E., "Systems modeling for the laser fusion-fission energy (LFE) power plant", Fusion Science and Technology, 56:647–651, (2009).
[14] D. James J., M. Gregory A., "Inertial confinement fusion", M. Gregory A., Wiley, (1982).
[15] Stacey WM., "Erratum: Capabilities of a DT tokamak fusion neutron source for driving a spent nuclear fuel transmutation reactor", Nuclear Fusion, 41:467, (2001).
[16] Di Sanzo C., Abdou M., Youssef M., "Transuranic transmutation efficiency of a small fusion-fission facility for spent uranium-oxide and Inert Matrix Fuels", Fusion Engineering and Design, 85:1488–1491, (2010).
[17] Wolkenhauer WC., Leonard Jr BR., Gore BF., Leonard Jr BRJ., Gore GF., "Transmutation of high-level radioactive waste with a controlled thermonuclear reactor", Battelle Pacific Northwest Labs., Richland, Wash.(USA), (1973).
[18] Betha HA., "The fusion hybrid", Physics Today, 32:44–51, (1979).
[19] Feng KM., Huang JH., "Transmutation of the actinide neptunium-237 with a hybrid reactor", Fusion Engineering and Design, 29:64–68, (1995).
[20] Feng KM., Zhang GS., "Transmutation of transuranic actinides in a spherical torus tokamak fusion reactor", Nuclear Fusion, 43:756–760, (2003).
[21] Bertel E., Dujardin T., "Management of Recyclable Fissile and Fertile Materials", NIA No. 6107, (2007).
[22] Stacey W., "Resolution of Fission and Fusion Technology Integration Issues: An Upgraded Design Concept for the Subcritical Advanced Burner Reactor", Nuclear Technology, 187:15–43, (2014).
[23] Tait JC., Gauld IC., Wilkin GB., "Derivation of initial radionuclide inventories for the safety assessment of the disposal of used CANDU(R) fuel", Atomic Energy of Canada Limited, AECL (Report), (1989).

[24] Nathan A.J., Scobell A., Atomic Energy of Canada Limited Ontario (Canada) CR (1994); Environmental Impact Statement on the concept for disposal of Canada’s nuclear fuel waste. Canada.

[25] Di Pace L., Natalizio A., "A radio toxicity index for fusion waste", Proceedings of the International Conference on Radioactive Waste Management and Environmental Remediation, ICEM, 1:395–400, (2003).

[26] P. Denise B., "MCNPX USER ’ S MANUAL", LA-CP-07-1473, (2008).

[27] ATOMSTPOYEXPORT, "Bushehr NPP Unit 1 Final Safety Analysis Report, Chapter 4", Moscow, (2007).

[28] Gera F., "The classification of radioactive wastes", Health Physics, 27:113–121, (1974).

[29] Rahmani Y., “Reloading pattern optimization of VVER-1000 reactors in transient cycles using genetic algorithm”, Annals of Nuclear Energy, 108:24–41, (2017).