EVALUATION OF SPENT FUEL INVENTORY AND RADIOACTIVITY FOR CANDU TYPE FUEL BUNDLES CONTAINING DIFFERENT U-BASED COMPOSITIONS

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Abstract

CANDU technology is a mature, well-proven nuclear technology, CANDU reactors being characterized by a high level of safety and security, but also having an evolutionary potential in terms of proliferation resistance, versatility for adaptation to different fuel cycles which ensures a superior use of nuclear fuel resources. The paper investigated spent fuel inventory and radioactivity at the End-of-Irradiation for some U-based fuels, as follows: Natural Uranium (NU), Slightly Enriched Uranium (SEU), Recovered Uranium (RU) and Natural Uranium Equivalent (NUE). For the proposed analysis, two fuel bundle projects have been considered, namely: CANDU standard fuel bundle and a CANDU type fuel bundle with 43 fuel elements, CN43, developed by Nuclear Fuel Performances Group at RATEN ICN. Fuel irradiation was simulated by using ORIGEN-S code, included in SCALE6 programmes package, up to burn-up degrees of 7 MWd/kgHE (NU and NUE fuels) and 11 MWd/kgHE (SEU and RU fuels), respectively. In all fuel bundle elements, identical fuel composition was assumed. In present work, the following spent fuel parameters were evaluated: radioactivity (total and in fuel components - actinides and fission products, respectively), fissile material inventory, and inventory of isotopes interesting from proliferation resistance perspective. A comparison of the spent fuel parameters was performed both for the same fuel bundle (CN43) with different fuel composition, and for different fuel bundles with the same fuel composition (NU).

Keywords: *CANDU type fuel bundle, U-based fuels, Radioactivity, Fissile inventory, Proliferation resistance*

Introduction

The rapid growth of the global demand for energy leads to an increase in the nuclear energy role and importance based on its ability to make a major contribution in solving the issues related to the availability of energy resources, climate changes, quality of the air and energy security.

In terms of nuclear energy sustainability, recycling represents a promising option for improving the efficiency in using the natural resources and reduction of radioactive waste accumulation. Recycling of reprocessed Uranium and Plutonium reduces the nuclear fuel cycle (NFC) impact on the environment not only by reducing the waste amount and toxicity, but also by reducing the requirements for Uranium mining and, implicitly leading to fuel resources better use.

Recovered Uranium is not a standard product and the U^{235} content may vary, depending on the degree of combustion on discharge and the type of reactor, several ways in which RU can be used to generate energy being known, such as: by enrichment; by mixing with High Enriched Uranium/ Low Enriched Uranium/NU; by direct recycling; by the combined application of enrichment and mixing with other fissile materials. The direct recycling of RU is an important option in countries conducting nuclear programmes based on Natural Uranium NFC. Some reactors have the potential to replace NU with SEU, in which case RU becomes very attractive given that it provides fuel with SEU characteristics without incurring the costs of enrichment stage [1].

A well-known feature of CANDU type reactors is their versatility to use alternative fuel cycles, other than NU, without requiring major changes in the basic design of the reactor. These alternative fuel cycles, also known as advanced fuel cycles, use a variety of fissile materials, including SEU with up to 1.2 wt% enrichment in U^{235}, RU, MOX and Thorium-based fuels. These fuels improve the economy of the fuel cycle by increasing the fuel burnup (which allows to reduce high costs in the resources consumption and final storage of spent fuel), provide increased operating margins (can be applied to increase the reactor power), reduction by 2-3 times the amount of fuel burned per unit of energy production (due to the relatively low enrichment), reduced fuel cycle costs, and greater flexibility in plant operation [2, 3].

CANDU technology versatility led in 2008 to the partnership agreement between CANDU Energy Inc., China National Nuclear Corporation's, Third Qinshan Nuclear Power Corporation, China North Nuclear Fuel Company, and Nuclear Power Institute of China to develop a new nuclear fuel project, called Natural Uranium Equivalent (NUE), and its implementation in China's CANDU reactors [4, 5].

NUE fuel offers the benefit of the simplest, fastest and cheapest way to efficiently use alternative fuel resources in operating CANDU reactors without changes to the reactor project, its operation and the basis for licensing. NUE fuel is a mixture of RU and Depleted Uranium (DU) oxides with behaviour and performance similar to that of the NU fuel [6]. RU and DU use in the NUE fuel manufacture for CANDU type reactors is the first important and necessary step in the transition to a closed fuel cycle (see Fig. 1).

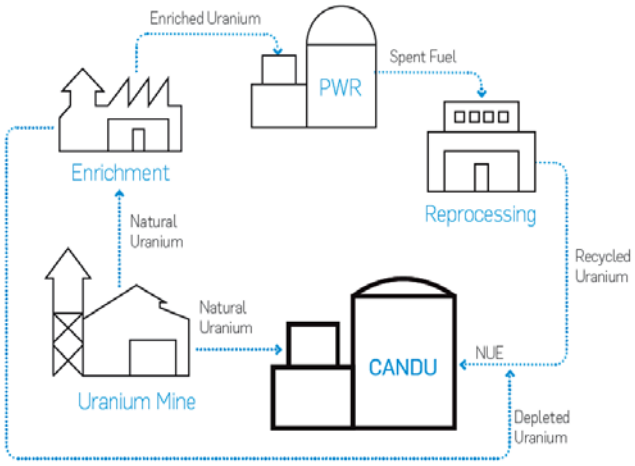


Fig. 1. Closed NFC with CANDU type reactor operating with NUE fuel [7]

The present work aimed to carry out a comparative study of different U-based fuels irradiated in CANDU type reactor conditions based on estimation of the spent fuel inventory and radioactivity at the End-of-Irradiation (EOI) before discharging from the reactor core and transfer to the cooling pool for intermediate storage. In terms of spent fuel inventory, the fissile isotopes (U^{235} and Pu^{239}) and the isotopes interesting from proliferation resistance perspective (Pu^{238}, Pu^{240}, and Pu^{241}) were considered.

Two CANDU type fuel bundle projects were selected for this study, namely: CANDU standard fuel bundle (C37) containing NU, and CANDU New 43 (CN43) fuel bundle developed by the Nuclear Fuel Performance group at RATEN ICN Pitesti [8], aiming to ensure a perfect compatibility with the fuel bundle currently used in Cernavoda Nuclear Power Plant (NPP) reactors.

Fuel burnup was simulated by means of ORIGEN-S code, included in SCALE6 programmes package [9] (developed by Oak Ridge National Laboratory, USA), assuming that all bundle fuel elements contain the same fuel composition. A comparison of the spent fuel parameters of interest has been performed, both for the same fuel composition (NU) in different fuel bundle projects, and for different fuel compositions in the same fuel bundle project (CN43).

Fuel bundle projects selected for analysis

CANDU type fuel bundle projects have the same cylindrical shape, are composed by fuel elements arranged on concentric rings and one central fuel element, their evolution being marked by increasing of the fuel elements number.

In June 1962, at Rolphton near the Chalk River (Canada), the NPD (Nuclear Power Demonstration) reactor was commissioned and started to operate using 7-element fuel bundles in the outer zone and 19-element fuel bundles in the inner zone; NPD reactor was the first Canadian power reactor and later became the prototype for the CANDU (Canada Deuterium-Uranium) reactor.

The 37-element CANDU fuel bundle was developed for the 750 MWe reactors operating at Bruce NPP (Canada) and became the CANDU standard fuel bundle used for the 600 MWe CANDU reactors in Canada (Gentilly) and other countries (Argentina, China, India, Pakistan, Romania and South Korea).

It is composed by 37 identical fuel elements arranged on 3 concentric rings (of 6, 12 and 18 elements, respectively) and one central element [10], as can be seen in Fig. 2. Each fuel element consists of a column containing 31 sintered NU fuel pellets inside a sealed zirconium alloy tube. The fuel elements are stiffened in the bundle assembly by two end plates, on the outer ring fuel elements being welded bearing pads for bundle easy sliding inside the pressure tube and to ensure a space for the coolant circulation. The fuel bundle is approximately 0.5 m long and 10 cm in diameter, with a sheath of 0.4 mm thick, and weighs about 24 kg.



Fig. 2. CANDU standard fuel bundle (C37) view [10]

CANDU New 43 (CN43) fuel bundle preliminary project [8] was developed by the Nuclear Fuel Performance Group at RATEN ICN, aiming a perfect compatibility with the fuel bundles currently used in Cernavoda NPP and pursuing the following objectives: increasing the fuel burn-up degree, reducing the amount of spent fuel destined for storage, increased resistance to power ramps and failure, increased safety in operation, improving the previously developed fuel bundle project generically called RU43 [11].

CN43 fuel bundle contains 43 identical elements arranged on 3 concentric rings of 7, 14, and 21 elements, respectively, around a central element (Fig. 3). Each fuel element contains 34 sintered fuel pellets inside a zircalloy-4 tube having about 50 cm in long and 10 mm in diameter, with a sheath of 0.36 mm thick, the fuel bundle weighing about 24 kg [8]. The fuel elements diameter is smaller comparatively with the standard CANDU fuel element one.

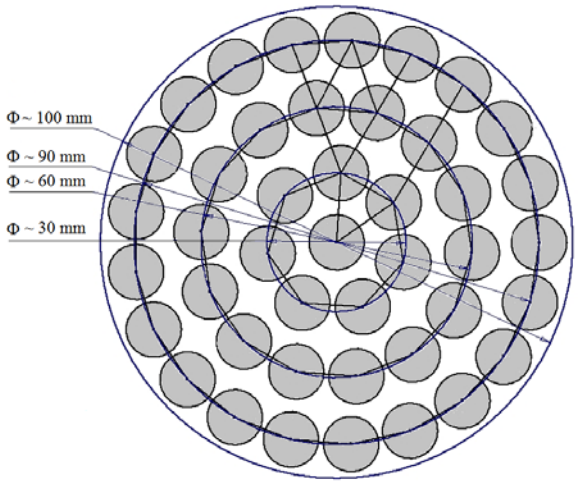


Fig. 3. Arrangement of fuel elements in CN43 fuel bundle preliminary project [8]

U-based Fuel compositions selected for analysis

The following fuel compositions were selected for analysis: Natural Uranium fuel [12]; Slightly Enriched Uranium fuel 1.0 wt% enriched in U^{235} [13]; Recycled Uranium fuel having 0.02 wt% U^{234}, 1.0 wt% U^{235} and 0.2 wt% U^{236} [13-16]; Natural Uranium Equivalent fuel containing a mixture of 60% SEU and 40% DU [13, 17].

According to the CN43 fuel bundle preliminary design [8], UO_2 mass per bundle is ~ 21 kg, the fuel pellets density being 10.6 g/cc, and Zy-4 total mass per bundle is ~ 2 kg, the density of the sheaths being 6.54 g/cc. A simplifying hypothesis from the neutronic lattice cell calculations was adopted, considering that the sheaths and the compact fuel pellets column extend along the entire length of the bundle (~ 50 cm), entire mass of Zy-4 being concentrated in the sheaths. The model used a ″low″ fuel density (10.18 g/cc), and an increased density for sheaths, 7.95 g/cc [14, 17].

For each fuel composition, the Uranium isotopes and O_2 weights in fuel were established and the material initial inventory is presented in Table 1, together with the U-based fuels identification.

Table 1. Initial inventory in selected U-based fuels, [12, 13]

	U-based fuel				
	C37 U	**CN43 U**	**CN43 SEU**	**CN43 RU**	**CN43 NUE**
Enrichment in U^{235} [wt%]	0.71	0.71	1.0	1.0	0.714
U^{234} [kg]	0	0	0.015	0.004	0.001
U^{235} [kg]	0.138	0.135	0.188	0.188	0.134
U^{236} [kg]	0	0	0.062	0.037	0.044
U^{238} [kg]	19.36	18.66	18.53	18.56	18.61
O_2 [kg]	2.620	2.525	2.525	2.525	2.525
Zy [kg]	2.144	2.237	2.237	2.237	2.237
UO_2 [kg]	22.11	21.32	21.32	21.32	21.32
Fuel bundle [kg]	24.26	23.55	23.55	23.55	23.55

The material composition of the bundle sheath made of Zirconium (Zr), alloying elements (Tin, Iron, Chromium, Nickel) and some impurities (Carbon and Oxygen) for the two considered fuel bundle projects is given in Table 2.

Table 2. Fuel bundle projects sheath composition, [12, 13]

Fuel bundle	**C37**	**CN43**
Element	Mass [kg]	Mass [kg]
Zirconium (Zr)	2.103	2.194
Alloying elements		
Tin (Sn)	$3.109 \cdot 10^{-2}$	$3.244 \cdot 10^{-2}$
Iron (Fe)	$3.645 \cdot 10^{-3}$	$3.803 \cdot 10^{-3}$
Chromium (Cr)	$2.144 \cdot 10^{-3}$	$2.237 \cdot 10^{-3}$
Nickel (Ni)	$1.179 \cdot 10^{-3}$	$1.230 \cdot 10^{-3}$
Impurities		
Carbon (C)	$4.074 \cdot 10^{-4}$	$4.250 \cdot 10^{-4}$
Oxygen (O)	$2.573 \cdot 10^{-3}$	$2.684 \cdot 10^{-3}$

Results and discussions

The proposed analysis results presented in the following are based on the lattice cell neutronic computations, as well as on previous burn-up calculations carried out for some U-based fuel compositions [12-15, 17].

The discharge burn-up degree varies with the fuel composition as follows: 6.650 MWd/kgHE for NU fuel, 10.850 MWd/kgHE for SEU fuel with 1.0 wt% enrichment in U^{235}, 10.500 MWd/kgHE for RU fuel with 1.0 wt% enrichment in U^{235}, and 6.300 MWd/kgHE for NUE fuel, respectively.

CANDU reactor specific conditions of irradiation have been simulated using the ORIGEN-S code [9] up to burn-up degrees of 7 MWd/kgHE (NU and NUE fuels) and 11 MWd/kg HE (SEU and RU fuels), respectively. The fuel irradiation was performed at 34.644 kW/kgHE specific burn-up power. By using DRAGON3.05E and WIMS programs, the spectral indices required to simulate fuel burn-up were previously obtained [14, 17].

The present comparative analysis is carried out based on evaluation of the U-based fuels radioactivity, fissile isotopes (U^{235} and Pu^{239}) inventory, and the inventory of isotopes of interest for proliferation resistance (Pu^{238}, Pu^{240} and Pu^{241}). The spent fuel radioactivity was evaluated both as total radioactivity characterizing the fuel, and values characterizing the fuel components (i.e. actinides and fission products). The interest parameters values were considered at the End-of-Irradiation (EoI).

Spent fuel inventory

Table 3 and Table 4 present the fissile material inventory and the inventory of the isotopes interesting from the proliferation resistance perspective, respectively, estimated for the C37 and CN43 fuel bundle projects and the selected U-based fuels.

Table 3. Fissile material inventory for considered U-based fuels at EoI

Fuel / Isotope	**Fissile inventory [g/assembly]**		
	U^{235}	Pu^{239}	**Total**
C37U	32.63	24.47	**57.10**
CN43U	27.58	22.59	**50.17**
CN43SEU	23.15	22.64	**45.79**
CN43RU	22.15	23.16	**45.31**
CN43NUE	27.93	23.07	**51.00**

The highest inventory of fissile isotopes was obtained for C37 reference fuel bundle (57 g/assembly) in comparison with the amounts characterizing CN43 fuel bundle, a relative difference of 11% being calculated for the comparison with CN43NUE fuel (51 g/assembly - the highest fissile content among the CN43 fuel bundle cases). The lowest fissile material content was estimated for the CN43 fuel bundle with RU fuel.

The fissile inventory reduces with increasing of fuel irradiation, due to higher consumption of U^{235} (at EoI against beginning of irradiation: ~ 65% lower content for NU and NUE fuels, and ~ 80% lower content for SEU and RU fuels, respectively) compared to Pu^{239} accumulation (at EoI against beginning of irradiation: ~ 30% higher content for NU and NUE fuels, and ~ 40% higher content for SEU and RU fuels, respectively). For the total fissile content evolution with irradiation in CN43fuel bundle cases, the relative differences calculated at EoI (against beginning of irradiation) registered ~50% for NU and NUE fuels, and ~70% for SEU and RU fuels, respectively.

Table 4. Inventory of isotopes of proliferation resistance interest for considered U-based fuels at EoI

Fuel / Isotope	**Inventory of isotopes interesting for proliferation resistance [g/assembly]**			
	Pu^{238}	Pu^{240}	Pu^{241}	**Total**
C37U	0.10	20.55	1.06	**21.71**
CN43U	0.02	21.16	1.27	**22.45**
CN43SEU	0.23	27.60	2.90	**30.73**
CN43RU	0.17	28.43	3.03	**31.62**
CN43NUE	0.10	21.69	1.31	**23.09**

The inventory of Pu^{238}, Pu^{240} and Pu^{241} isotopes is higher in CN43 fuel bundle cases than the C37U (21.71 g/assembly), a relative difference of 30% being obtained for the comparison with CN43RU fuel (31.62 g/assembly - the highest content of isotopes interesting for proliferation resistance among the CN43 fuel bundle cases).

The lowest content of isotopes interesting from proliferation resistance perspective was estimated for the CN43 fuel bundle with NU fuel (22.45 g/assembly - only 3% higher than the C37U one).

The amount of isotopes interesting for non-proliferation increases significantly with increasing fuel irradiation, the relative differences calculated for CN43 fuel bundles cases at EoI against beginning of irradiation being ~ 80% for NU and NUE fuels, and ~ 90% for SEU and RU fuels, respectively. The total inventory of isotopes interesting for non-proliferation is dominated by the evolution of Pu^{240} inventory, representing ~ 90% from the total amount. CN43 fuel bundles containing SEU or RU fuel are characterized by ~ 25% higher inventory of isotopes interesting for non-proliferation comparatively with the CN43 fuel bundles containing NU or NUE fuel.

Spent fuel radioactivity

The radioactivity characterizing the spent fuel in the considered fuel bundle projects is presented in following. Table 5 contains the estimated values of the total radioactivity in the spent fuel, and the radioactivity of actinides and fission products, respectively.

Table 5. Inventory of isotopes of proliferation resistance interest for considered U-based fuels at EoI

U-based fuel	**Radioactivity [Ci/assembly]**		
	Actinides	Fission Products	Fuel
C37U	$9.250 \cdot 10^5$	$3.088 \cdot 10^6$	$4.014 \cdot 10^6$
CN43U	$9.820 \cdot 10^5$	$2.903 \cdot 10^6$	$3.886 \cdot 10^6$
CN43SEU	$9.809 \cdot 10^5$	$2.929 \cdot 10^6$	$3.911 \cdot 10^6$
CN43RU	$1.017 \cdot 10^6$	$2.991 \cdot 10^6$	$4.009 \cdot 10^6$
CN43NUE	$1.007 \cdot 10^6$	$2.968 \cdot 10^6$	$3.976 \cdot 10^6$

At a first glance, it can be noticed that the estimated spent fuel total radioactivity for the considered U-based fuels does not differ significantly from case to case, the relative difference between values being less than 5%. Among the CN43 spent fuels, the highest total radioactivity was estimated for CN43RU, and CN43U registered the lowest total radioactivity (3% lower than the one estimated for CN43RU). However, the highest value of the spent fuel total radioactivity was obtained for C37U fuel, only 0.14 % higher compared to the CN43RU fuel one.

Continuing the comparison at the level of radioactivity in fuel components between C37U and CN43 fuel cases, some aspects should be mentioned.

Actinides radioactivity is higher in CN43 spent fuels in comparison with C37U spent fuel. The highest values were obtained for CN43RU fuel and CN43NUE fuel (lower by only 1%), the lowest values being estimated for C37U fuel (9% lower than CN43RU fuel case).

On the contrary, the comparison between fission products radioactivity estimated for C37U and CN43 spent fuels brings in advantage the reference case characterized by a value 3% higher than CN43RU one (the highest radioactivity in fission products among the CN43 fuels) and 6% higher than the one of CN43U fuel (the lowest radioactivity in fission products among the CN43 fuels).

The spent fuel total radioactivity and radioactivity in fuel components (actinides and fission products) evolution at EoI and during the fuel irradiation for the considered fuel bundle projects are comparatively represented in Figs. 4-8.

As the fuel irradiation increases, the total radioactivity and the radioactivity of actinides become higher. Meantime, the radioactivity of fission products has a slightly descending evolution, but this decrease is too small to compensate for the increase in the fuel total radioactivity due to increasing of the actinides radioactivity.

The contribution of actinides radioactivity to the total radioactivity in fuel increases with fuel irradiation: NU and NUE fuels - from 21% to 25%; SEU and RU fuels - from 16% to 25%. Regarding the contribution of fission products radioactivity to the total radioactivity in fuel, we are dealing with a decrease during the fuel irradiation: NU and NUE fuels - from 79% to 75%; SEU and RU fuels - from 83% to 75%.

The comparative analysis of the results was performed using the relative differences corresponding to the comparison of the spent fuel parameters of interest (isotopic inventory, radioactivity) estimated at the End of Irradiation. The parameters of interest were compared both for the same fuel bundle project (CN43 fuel bundle) with different fuels, and for different fuel bundle projects and the same fuel (NU).

Table 6 reveals the relative differences calculated for before mentioned comparative analysis.

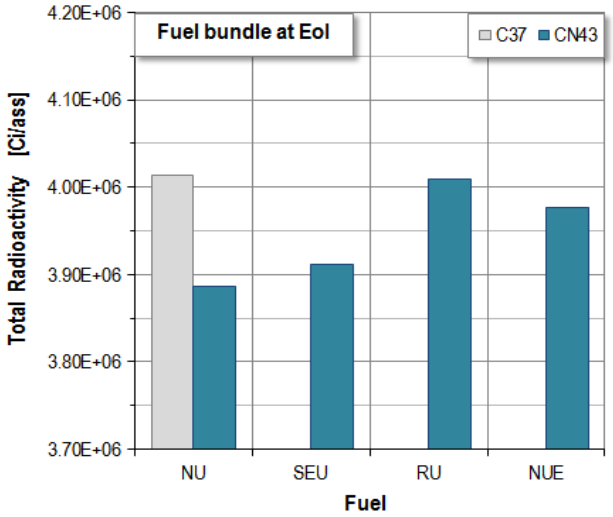


Figure 4 Spent fuel total radioactivity at EOI for U-based fuels

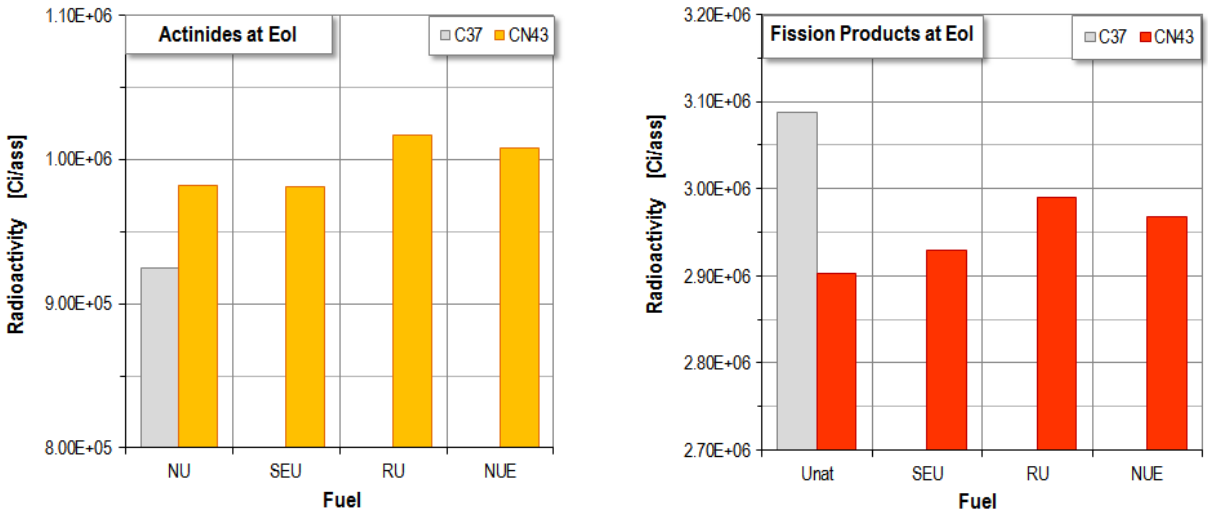


Figure 5 Fuel components radioactivity at EOI for U-based fuels
actinides (left) and fission products (right)

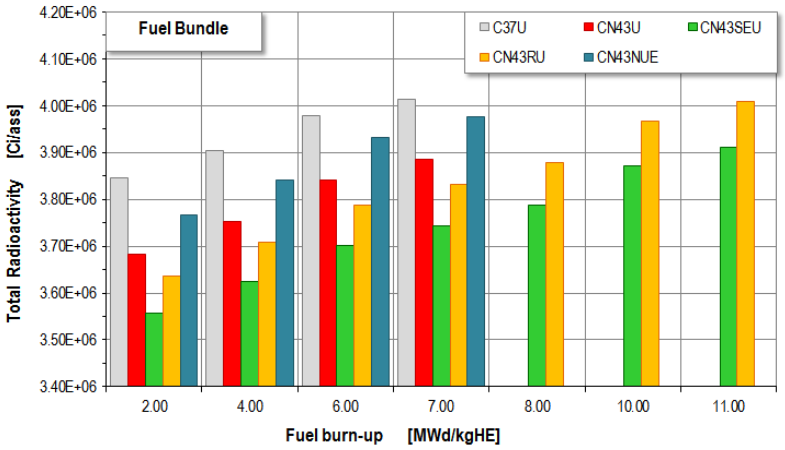


Figure 6 Spent fuel total radioactivity evolution during irradiation for U-based fuels

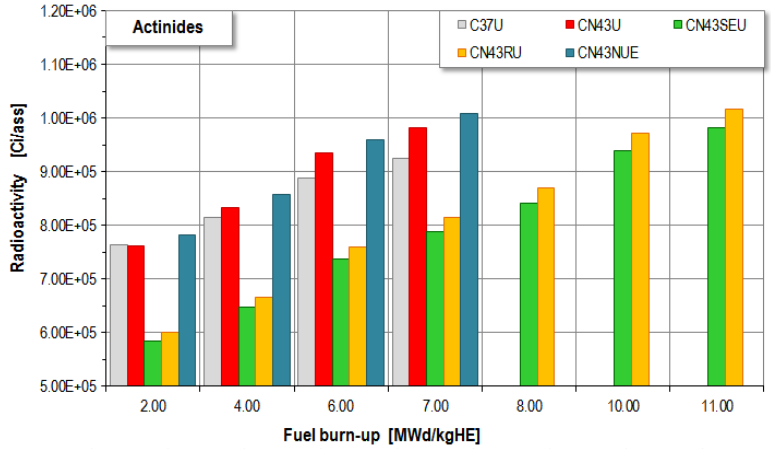


Figure 7 Actinides radioactivity evolution during irradiation for U-based fuels

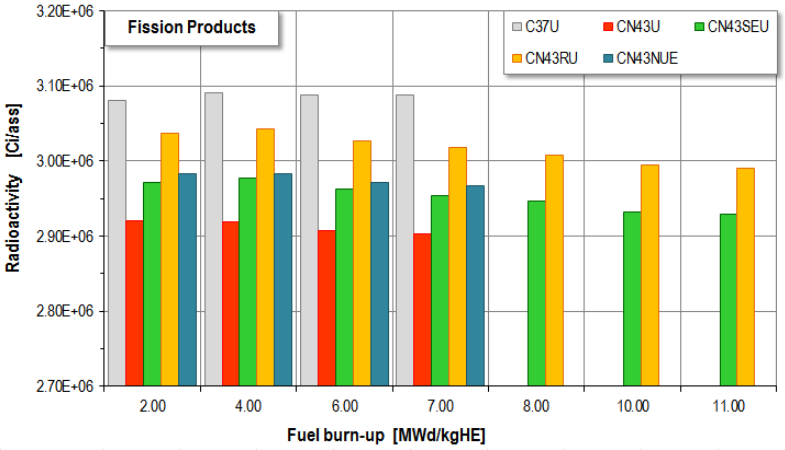


Figure 8 Fission products radioactivity evolution during irradiation for U-based fuels

Table 6 – Comparative analysis for the spent fuel parameters of interest at EoI

Comparison	Relative differences [%]		
	U^{235}+Pu^{239} inventory	Pu^{238}+Pu^{240}+Pu^{241} inventory	Total radioactivity
C37U vs CN43U	12.1	- 3.3	3.2
CN43SEU vs CN43U	- 8.7	27.0	0.6
CN43RU vs CN43U	- 9.7	29.0	3.1
CN43RU vs CN43SEU	- 1.1	2.8	2.4
CN43RU vs CN43NUE	- 11.1	27.0	0.8
CN43NUE vs CN43U	1.6	2.8	2.3
CN43NUE vs CN43SEU	10.2	- 25.0	1.6

Conclusions

The paper investigated the behaviour of the CN43 innovative fuel bundle containing U-based fuels to fuel irradiation in CANDU reactor specific conditions, based on the estimation of spent fuel isotopic inventory and radioactivity. As reference, the 37-element CANDU standard fuel bundle with NU fuel was considered.

CN43 innovative fuel bundle is a CANDU type fuel bundle preliminary project with 43 elements, developed at RATEN ICN Piteşti. The fuel elements are identical and have a smaller diameter compared to that of the element in the 37-element CANDU standard fuel bundle. The study assumed the same fuel composition in all elements of the fuel bundle. Four fuel compositions were considered for study, namely: NU fuel, SEU fuel 1.0 wt% enriched in U^{235}, RU fuel 1.0 wt% enriched in U^{235}, and NUE fuel containing 60% SEU and 40% DU.

The U-based fuels irradiation was simulated by using the ORIGEN-S burn-up code included in SCALE6 software package, the fuel being irradiated at a specific burn-up power of 34.644 kW/kgHE, as follows: NU and NUE fuels - up to 7 MWd/kgHE; SEU and RU fuels - up to 11 MWd/kgHE.

The parameters of interest for the study were spent fuel radioactivity (total radioactivity in the fuel and in fuel components – actinides and fission products), fissile isotopes inventory (U^{235} and Pu^{239}), and inventory of isotopes interesting from proliferation resistance perspective (Pu^{238}, Pu^{240}, Pu^{241}), respectively.

As the fuel irradiation increases, U^{235} consumption is higher than Pu^{239} accumulation leading to a reduction in the fissile inventory. At the end of irradiation, the total fissile inventory reduces by 44% for C37U, 48% for CN43U and CN43NUE fuels, and 67% for CN43SEU and CN43RU fuels, respectively, in comparison with the initial fissile inventory (U^{235} only). The highest fissile content was associated to C37U fuel, 57 g/assembly (33 g/ass U^{235} and 24 g/ass Pu^{239}), 12% higher than the CN43U fuel one.

The inventory of fissile isotopes for CN43 fuel bundle with SEU or RU fuel was 9% -11% lower compared to that obtained for CN43 fuel bundles with NU or NUE fuel. For the CN43 fuel bundle with NUE fuel, the highest fissile material content was recorded, 51 g/assembly (28 g/ass U^{235} and 23 g/ass Pu^{239}).

The inventory of isotopes interesting for non-proliferation increases significantly as the fuel irradiation and enrichment in U^{235} increase. This time, the CN43 fuel bundles were characterized by up to 30% higher inventory of isotopes interesting for non-proliferation (CN43RU fuel case) comparatively with the reference case, C37U (21.7 g/assembly). The highest inventory of the Pu^{238}, Pu^{240}, Pu^{241} isotopes was obtained for CN43RU fuel (31.6 g/assembly), the lowest inventory being associated with CN43U fuel (22.4 g/assembly). It should be mentioned that Pu^{240} inventory represents more than 90% of the total inventory of the isotopes interesting from proliferation resistance perspective.

The spent fuel total radioactivity increases during irradiation, mainly due to a significant increase in the contribution of actinide radioactivity by up to 25%, accompanied by a downward evolution in the contribution of fission product radioactivity from 84% to 75%. At the end of irradiation, the spent fuel radioactivity values estimated for the considered fuel bundle projects and U-based fuels were only slightly different, C37U fuel being characterized by the highest total radioactivity, 3% higher comparatively with the CN43U fuel one. As regarding the CN43 fuels, the highest spent fuel total radioactivity was obtained in CN43RU fuel, about 3% higher in comparison with CN43U fuel having the lowest total radioactivity.

An interesting observation is related on the behaviour of the radioactivity in fuel components. While the actinides radioactivity is higher for CN43 fuels (the highest value being recorded for CN43RU fuel - 9% higher than that obtained for C37U fuel), the highest value of the fission products radioactivity was estimated for C37U fuel (6% higher than the value associated with CN43U fuel, and 3% higher than the one obtained for CN43RU fuel).

The use of the innovative CN43 fuel bundle containing U-based fuels in CANDU reactors does not require additional radiation protection measures than those already implemented for the use of standard CANDU fuel bundle with NU fuel.

Although at the end of irradiation the fissile material inventory does not exceed that of the C37 standard fuel bundle, the CN43 fuel bundle containing SEU or RU fuel showed an increase in the inventory of isotopes interesting for non-proliferation by 30%.

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