BURNUP PENALTIES FOR SOME ATF FUEL OPTIONS IN A CANDU TYPE REACTOR

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Abstract

The paper evaluates the burnup penalties associated to the doping of actual CANDU standard fuel with metallic oxides of niobium, chromium and titanium. The irradiation experimental program early performed in RATEN ICN showed that the presence of these oxide-based additives in the Natural Uranium (NU) UO_2 fuel allows for increasing the fuel grain size and density, leading to a better fission products retention during postulated accidents. Up to a critical concentration of 0.16% M/U, the burnup penalties are still acceptable and situated in a range of several percent. Adding a 20 μm thick chromium layer on the fuel clad significantly worsens the discharge burnup and penalties increase to an unacceptable 20%, if NU fuel is still used. The using of Slightly Enriched Uranium (SEU) instead of NU is proposed to compensate for burnup losses, in the frame of Accident Tolerant Fuel-Natural Uranium Equivalent (ATF-NUE) concept.

Keywords: *CANDU, Burnup penalty, Metallic oxides dopants, Chromium, ATF-NUE*

Introduction

The Romanian nuclear power energy sector is represented by the two 700 MWe output CANDU 6 units in operation at Cernavoda Nuclear Power Plant (NPP), while the commissioning of other two similar units still delays for a long time. Units 1 and 2 provide about 20% of the total electricity generation in the national grid.

The average discharge burnup (ADB) for a typical CANDU 6 reactor is about 7.2 MWd/kgU [1], quite small compared to the Light Water Reactors (LWR), for example. Increasing the ADB and, consequently, CANDU reactor efficiency requires the fuel enrichment and, consequently, a longer period of the fuel bundles' residence in the reactor core. Thus, the increasing of burnup time comes together with challenges like: fuel and clad swelling, accumulation of larger amounts of fission gases, accelerating the stress corrosion cracking (SCC), oxidation, and embrittlement processes etc. To cope with these higher burnup drawbacks and also, to achieve an improved tolerance to loss of active cooling, new fuel concepts have been proposed, generally known as Accident Tolerant Fuels (ATF), [2 - 4]. A way to prevent higher pressure and accumulation of the fission gases, for example, is to enhance retention of the fission products (FP) by using oxide additives like Nb_2O_5, TiO_2 and Cr_2O_3 in the UO_2 fuel matrix, [5, 6]. The irradiation experimental program early performed in RATEN ICN during 1996-2000 showed that placing these oxide-based additives in the UO_2 fuel allow for increasing the fuel grain size and density, helping in a better FP retention and lowering the fission gas pressure inside the fuel elements. On the other side, the ATF concepts also involve the fuel clad strengthening in order to efficiently cope with oxidation phenomena during accident conditions. This objective can be met by coating the clad with pure metals (Cr, Cr-Al alloy, FeCrAl) or ceramic materials (nitrides: CrN, TiN, TiAlN, CrAlN) with suitable thicknesses, [2].

As the oxide additives and clad metallic layers act as neutron absorbers, their penalties on the ADB must be evaluated. The goal of the paper is to evaluate these penalties in a CANDU reactor core fed with some variants of ATF fuel, in a Natural Uranium (NU) UO_2 matrix, doped with metallic oxides of Niobium, Chromium and Titanium, with or without clad coating (20 μm thick pure Chromium layer). Additionally, in order to counteract the burnup penalties and achieve an equivalent exit burnup similar to the CANDU standard fuel, uranium enrichment was slightly increased accordingly, for every configuration.

Working Configurations

Three basic sorts of metallic oxides were considered, namely: Nb_2O_5, Cr_2O_3 and TiO_2. These additives were supposed to be present in an UO_2 fuel matrix, this resulting in three types of doped nuclear fuel whose characteristics are presented in Table 1. A theoretical density (TD) of 10.96 g/cm^3 for UO_2 was considered [7], and an unique ratio Metal/Uranium (M/U) of 0.16wt% was used in analysis. The CANDU 37-rod standard fuel design was also considered as reference, Config. 1 (NU) and the same fuel carrier, namely the C37 bundle project was used overall.

The M/U ratio was chosen according to the experimental results and considerations expressed in [5, 6], pursuing a fair compromise in order to maximize the fuel density, the size of grains for a better fission gas retention, and mechanical behavior. Apart from oxides from Table 1, a very small amount (0.02 wt% Al/U) of Al_2O_3 was also considered to be present overall in the fuel, in order to enhance grain growth during fabrication, [8, 9].

Table 1.Working Configurations and Fuel Characteristics

Config.#	1	2	3	4	5	6	7
Acronym	NU	Nb	Cr	Ti	Nb +20μm Cr	Cr +20μm Cr	Ti +20μm Cr
Fuel matrix	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2
Additive oxide	-	Nb_2O_5	Cr_2O_3	TiO_2	Nb_2O_5,	Cr_2O_3	TiO_2
Metal/Uraniu (wt%)	0	0.16	0.16	0.16	0.16	0.16	0.16
Cr Clad Coating Thickness (μm)	-	-	-	-	20	20	20
Fuel density (% of TD of UO_2)	96.7 [7]	98.5 [5]	98.2 [5]	98.7 [5]	98.5 [5]	98.2 [5]	98.7 [5]

Methodology Outlines

The lattice modelling was firstly carried out in order to obtain the neutronic properties. The basic unit of the CANDU reactor is the lattice cell containing the fuel bundle and associated coolant, pressure and calandria tubes, surrounded by a corresponding volume of moderator, as in Fig. 1. The lattice properties depend on the physical dimensions and material composition. The nuclear fuel burning process changes the lattice neutronic properties and these modifications are captured in macroscopic effective cross section tables with respect to the burnup. One set of macroscopic effective cross sections was generated for every fuel configuration from Table 1, on 43 steps of 9 days each and a specific fuel power of 31.5 MW/kgU, [10].

Lattice burnup calculations have been performed using the WIMS-D5B code [11] and associated IAEA nuclear data library [12].

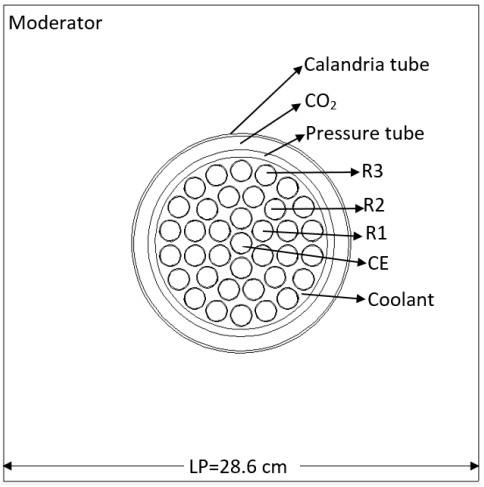


Fig. 1. CANDU lattice cell (at scale)

In Fig. 1, where the CANDU lattice cell is represented, CE, R1, R2, and R3 denotes the central fuel element, followed by the element fuel rings (internal, intermediary, and external), while LP is the lattice pitch (28.6 cm). Fig. 2 illustrates a frontal view of the C37 bundle geometry, a RATEN ICN approach to a CANDU 37-rods bundle design, used as carrier for the nuclear fuel overall.

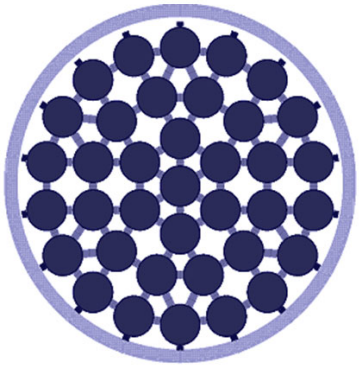


Fig. 2. C37 fuel bundle

The cross section table sets were introduced one by one in a standard CANDU 6 core model [13, 14] adapted to the input of DIREN computer program [15-17], and then core burnup calculations in the *time average* (TA) approximation, [18], have been carried out. As all CANDU reactors are refueled on power and to take into account for the fuel burnup heterogeneity along with the refueling scheme, the TA approximation was developed. In the TA model, the core is conveniently subdivided into several irradiation regions (see in Fig. 3). Small digits (1 to 4) represent the burnup regions, while the larger ones (1 to 7) denote the light water Zone Control Unit (ZCU) power regions. The ZCU system is the first option to achieve a fine reactivity control during every Full Power Day (FPD) of operation. The standard 8-bundles shift was used, as shown in Fig. 4.

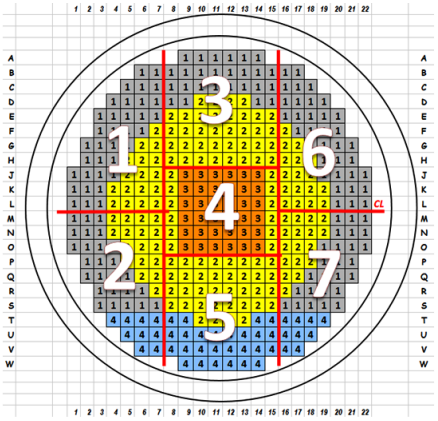


Fig. 3. Burnup regions along with ZCU power regions

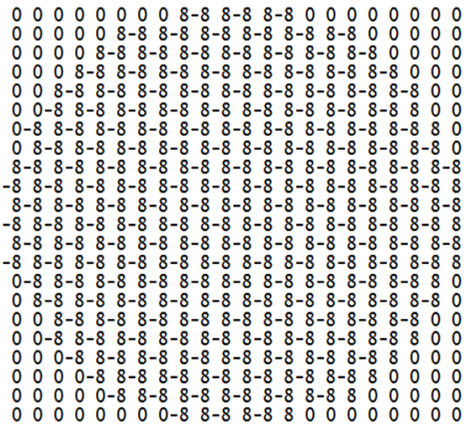


Fig. 4. Eight bundle shift scheme

Apart from the reference burnup and power distributions over the reactor core, the TA calculation also supply an Average Discharge Burnup (ADB) over the reactor core, whose penalties will be evaluated according to the additional absorber amount introduced in every considered configuration. As opposed to the lattice calculation where reflective boundary conditions are supposed (infinite lattice), the diffusion approximation implemented in the DIREN program takes into account for neutron leakage through an extrapolation length, thus it is expected that TA results to be more realistic than the lattice ones. According to the leakage consideration, lower values for ADB are expected to be supplied through 3D core calculations previously performed in [19] revealed that relatively small amounts of additional absorbing materials introduced in actual CANDU lattice with NU (0.711% U^{235}) may prevent refueling operations deployment if the actual 8-bundle shift scheme is preserved and no additional fissile added. In other words, the CANDU lattice long term ″sustainability″ in terms of reactivity and criticality asks for quite less additional absorbent, or to compensate it by more initial fissile material than that present in NU. As the refueling core calculations previously performed in [19] for similar configurations only partly succeeded, it is considered that actual lattice and TA core calculations to be enough for achieving the paper goal.

Lattice cell calculations results

The infinite multiplication constants evolution versus irradiation for the considered configurations is presented in Fig. 5. The instantaneous exit burnup value (i.e. the burnup corresponding to the k-inf=1) slowly decreases by burnup from 7.3 to 6.55MWd/kgU.

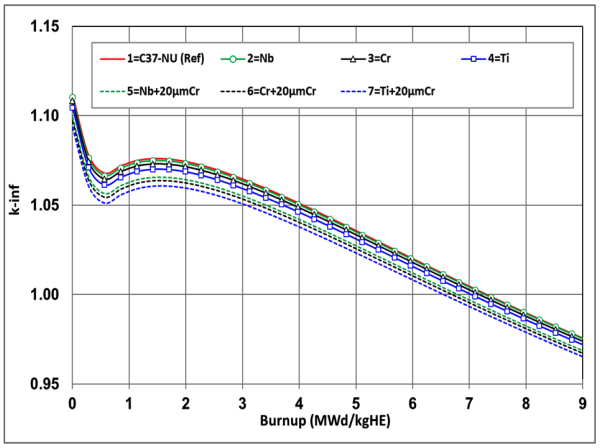


Fig. 5. Evolution of infinite multiplication constant with fuel irradiation

To have a better illustration of the burnup penalties, in Fig. 6 the burnup range of interest (6.5-7.5 MWD/kgU) was depicted. According to the Fig. 6, the instantaneous exit burnup values were extracted and presented in Table 2 along with the corresponding penalties. The burnup penalty is defined as difference between the reference instantaneous exit burnup value of NU (Config. 1) and the current value supplied by the doped Configs. 2-6. Relative differences in percent are also calculated and shown.

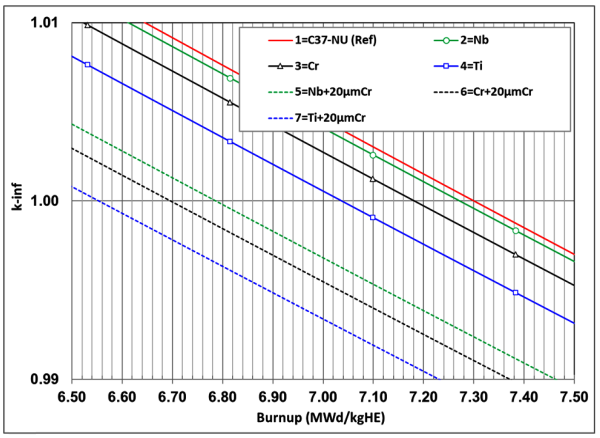


Fig. 6. Infinite multiplication constant evolution in the burnup interval 6.5-7.5 MWd/kgU

Table 2. Instantaneous exit burnup values and penalties

Config.#	1	2	3	4	5	6	7
Acronym	NU	Nb	Cr	Ti	Nb +20μm Cr	Cr +20μm Cr	Ti +20μm Cr
Instantaneous exit burnup (MWd/kgU)	**7.30**	7.28	7.18	7.04	6.79	6.70	6.55
Absolute penalty (MWd/kgU)	-	0.02	0.12	0.26	0.51	0.60	0.75
Relative penalty (%)	-	-0.3	-1.6	-3.6	-7.0	-8.2	-10.3

Taking in to account that all doped configurations have the same main dopant content (0.16 wt% M/U), the burnup penalty is only given by neutronic characteristics of every metal (Ni, Cr and Ti). Thus, Nb seems to be the least absorbent while Ti is the most absorbent. The absolute penalty increases to 0.75 MWd/kgU, this meaning about 10% of the standard NU instantaneous exit burnup. It can also be seen that the presence of a 20μm Cr layer on the clad significantly worsens the burnup by about 0.5 MWd/kgU overall. In this respect, the presence of a doping metal alone without any Cr layer on the clad can be considered still acceptable in terms of burnup penalties.

Core calculations results

The time average core calculations were performed separately, for every fuel configuration from Table 1.

Table 3 presents relevant core results like: average discharge burnup (ADB), maximum channel and bundle powers along with Radial Form Factor (RFF). RFF is a measure of power flattening over the reactor core, it being the ratio between the average and maximum powers and should be as close as possible to unity. A typical value reported for a CANDU 6 unit is 0.83, [18].

Table 3. Core time average results

Config.#	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Acronym	NU (Ref.)	Nb	Cr	Ti	Nb +20μm Cr	Cr +20μm Cr	Ti +20μm Cr
Core reactivity (mk)	**0.01**	0.02	0.04	0.06	0.0	0.04	0.06
Maximum channel power (MW)	**6.49**	6.50	6.51	6.53	6.55	6.54	6.53
Maximum bundle power (kW)	**787**	787	786	785	783	782	780
Radial Form Factor	**0.84**	0.83	0.83	0.83	0.83	0.83	0.83
Uranium mass per bundle (kg)	**19.0**	18.95	18.95	18.95	18.95	18.95	18.95
Dwell time (FPD[a])	**197**	195	188	178	160	152	138
Fuel consumption (bundles/FPD)	**15.4**	15.6	16.1	17.1	19.2	20.1	22.0
ADB (MWd/kgU)	**7.10**	7.03	6.79	6.42	5.76	5.48	5.00
Absolute penalty (MWd/kgU)	-	0.07	0.31	0.68	1.34	1.62	2.10
Relative penalty (%)	-	-1.0	-4.4	-9.6	-18.9	-22.8	-29.6

[a] Dwell time is the refueling time expected for a channel, on average

For all considered configurations, some of the core integral parameters have similar and close values (maximum channel and bundle powers, RFF and core reactivity). This means that all the configurations allow for operation in a similar manner. Differences appear when economic parameters like dwell time and ADB are extracted. The dwell time is the time when the *average channel* is expected to be refuelled, due to exhausting the initial fresh fuel reactivity excess. The concept of *average channel* is specific to the TA approximation, its neutronic properties being an average over the reactor core weighted by the target exit irradiation on every burnup region, see Fig.3. A typical TA CANDU 6 dwell time value is 192 Full Power Days (FPD), [20]. As the absorbent in form of doped oxide is added, the initial reactivity excess is more rapidly exhausted and the average fuel channel must be refuelled earlier and earlier. Thus, the dwell time is shortened to 138 FPD, a 2/3 from the reference value. Accordingly, the fuel consumption (bundles/FPD) increases from 15.4 to 22 bundles/FPD, 43% more than in the reference case. Therefore, the ultimate consequence of fuel doping is larger and larger penalties on ADB.

As opposed to lattice calculations, when penalties were rising slowly and linearly only up to 10%, this time the core results show that penalties on fuel burnup become quite important and may seriously affect the economics of the nuclear unit. A 20-30% reducing in ADB and, consequently in revenues per kilowatt-hour sold on the electricity market, could be unacceptable for the NPP owner, despite of safety benefits.

A fair compromise between safety gains through the fuel doping and associated burnup penalties is represented by the using of slightly enriched uranium (SEU), or with other words, an ATF Natural Uranium Equivalent (ATF-NUE) fuel. In this respect, the most absorbent configurations (5, 6, and 7 as in Table 1) were tailored with appropriate SEU amounts to meet the ADB of NU (~ 7.1 MWd/kgU). Due to an excellent neutron economy, CANDU design is able to annihilate the absorbing effects of doping with metals through the using of quite small enrichments over that of NU. The procedure to find out the appropriate ATF-NUE enrichment was to get the same instantaneous exit burnup as in the case of NU based on the lattice calculations. The new generated neutronic properties with SEU fuel were then introduced in the DIREN input to run a TA calculation and to find out the new ("equivalent") ADB values.

Table 4 summarizes core TA parameters of interest along with the initial enrichments needed to convert the Configurations 5, 6 and 7 in NUE ones (8, 9 and 10).

The resulted ADB values are, this time, a few percent larger than that of NU, assuring a comfortable equivalence while preserving safety parameters.

Table 4. Core time average results for ATF NUE configurations

Config.#	**1**	**8**	**9**	**10**
Acronym	NU	Nb +20µm Cr +0.74%SEU	Cr +20µmCr +0.745%SEU	Ti +20µmCr +0.753%SEU
Initial enrichment (%U235)	0.71	0.740	0.745	0.753
Core reactivity (mk)	0.01	0.05	0.01	0.02
Maximum channel power (MW)	6.49	6.48	6.46	6.45
Maximum bundle power (kW)	787	788	787	788
Radial Form Factor	0.84	0.84	0.84	0.84
Uranium mass per bundle (kgU)	19.0	18.95	18.95	18.95
Dwell time (FPD[a])	197	203	203	205
Fuel consumption (bundles/FPD)	15.4	15.0	15.0	14.9
ADB burnup (MWd/kgU)	7.10	7.30	7.33	7.38
ADBrelative to that of NU	-	+3%	+3%	+4%

Conclusions

The considered ATF fuel sorts based on the doping process with metals like Nb, Cr, Ti showed that the benefits for nuclear safety demonstrated through numerous experiments performed to now are accompanied by burnup penalties, which have been evaluated through neutronic calculations.

Up to a critical concentration of 0.16%M/U (earlier found as a solubility limit of Cr_2O_3 in UO_2) the burnup penalties are still acceptable and situated in a range of several percent. Adding a 20µm Chromium layer on the fuel clad significantly worsens the discharge burnup and penalties become unacceptable, if NU fuel is still used.

A fair compromise between safety gains through the fuel doping and associated burnup penalties is to use slightly enriched uranium (SEU), instead of NU, in the frame of so called ATF Natural Uranium Equivalent (ATF-NUE) fuel concept. The neutronic calculations revealed that quite small enrichments over that of NU, can suppress the associated doping penalties on fuel burnup.

Having an acceptable abundance on Earth, being relatively easier to be obtained than niobium and titanium, and having a moderate neutron absorption, chromium can be a solution for both the fuel doping and clad covering in order to achieve a robust ATF concept.

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