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Re-fueling the actinides ^{239}Pu,^{241}Am and ^{243}Am as burnable absorbers in the MTR-22 MW research reactor

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□ ABSTRACT □

The main objective of this paper is the re-fueling of the MTR-22MW reactor by the U_3O_8-Al Original Fuel Elements (OFEs) mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides as burnable absorbers. This procedure helps to consume some of the stored ^{239}Pu, and minimize the radiological impacts of the actinides ^{241}Am and ^{243}Am on the environment. The neutronic parameters such as: Reactivity ρ_{ex}, Control Plates Worth (CPsW), Shutdown Margin (SM), Shutdown Margin with first control plate failure (SM-1), Reactivity Safety Factor(RSF), neutron spectrum in the Central Neutronic Trap (CNT), in the Central Irradiation Box (CIB), in the Be reflector and Power Distribution Factors (PDFs) of the MTR-22MW reactor were re-evaluated using the MCNP4C transport code. The variation of the reactivity ρ_{ex} was studied as a function of the operation time of the reactor as well. The obtained results showed that the MTR-22 MW reactor can been operated with U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides within the safety conditions established in the design. Re-fueling of the MTR-22 MW reactor by U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides leads to reduce the enrichment with ^{235}Ufrom 19.7% to 10.1% for every load, and to burn 1187.71 g ^{239}Pu, 220.04 g ^{241}Am and 96.89 g ^{243}Am per year. These results contribute to enhance the proliferation resistance of radioactive materials.

Key words: MTR-22 MW reactor, neutronic parameters, minor actinide, MCNP4C code.

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إعادة تحميل الاكتنيدات ^{239}Pu و^{241}Am و^{243}Am كماصات قابلة للاحتراق في مفاعل البحث MTR–22 MW

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□ ملخّص □

إنَّ الهدف الرئيس لهذه الورقة هو إعادة تحميل المفاعل MTR–22MW بالوقود الأساسي U_3O_8–Al الممزوج بالعناصر الاكتنيدية ^{239}Pu و ^{241}Am و ^{243}Am كماصات نترونية قابلة للاحتراق (الانشطار). ويساعد هذا الإجراء في استهلاك قسم من البلوتونيوم ^{239}Pu المخزن، وتخفيض التأثيرات السلبية البيولوجية الضارة للإكتنيدات ^{241}Am و ^{243}Am في الوسط البيئي المحيط. وجرى حساب الأوساط النترونية للمفاعل MTR– 22 MW مثل: التفاعلية ρ_{ex}، ووثوقية صفائح التحكم (CPsW)، وهامش الإغلاق (SM)، وهامش الإغلاق بوجود صفيحة تحكم خارج قلب المفاعل (1–SM)، ومعامل تفاعلية الأمان (RSF)، والطيف النتروني في المصيدة النترونية المركزية (CNT) وصندوق التشعيع المركزي(CIB) وعاكس البيريليوم Be إضافة إلى توزع الاستطاعة للمفاعل MTR–22 MW باستخدام الكود MCNP4C. وإضافة إلى ذلك، درس تغير التفاعلية ρ_{ex} للمفاعل MTR–22 MW كتابع لزمن تشغيليه. وقد أظهرت النتائج أن المفاعل MTR–22 MW يمكن أن يعمل بالوقود الأساسي U_3O_8–Al الممزوج بالعناصر الاكتنيدية ^{239}Pu و^{241}Am و^{243}Am كماصات نترونية قابلة للاحتراق ضمن شروط الأمان المأخوذة في تصميم المفاعل، وإنَّ تحميل المفاعل MTR–22 MW بالوقود الأساسي U_3O_8–Al الممزوج بالعناصر الاكتنيدية ^{239}Pu و^{241}Am و^{243}Am يودي إلى تخفيض الإغناء باليورانيوم ^{235}U من 19.7%إلى 10.1% لكل حمل، وإلى حرق 1187.71 غرام من ^{239}Pu، و 220.04 غرام من ^{241}Am و96.89 غرام من ^{243}Am في السنة. وتساهم هذه النتائج في تعزيز مبدأ مقاومة الوفرة من المواد المشعة.

الكلمات المفتاحية: المفاعلMW 22–MTR، الوسطاء النترونية، الاكتينيدات الثانوية والكود MCNP4C.

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Introduction

During nuclear energy generation highly radiotoxic by products such as the Minor Actinides (MAs) is formed, which accumulate in spent fuel. Minor actinides transmutation can take two forms: either the MAs nuclei undergo fission or yields fission products that are shorter lived or capture a neutron and are transmuted into another heavy nuclide. The main MAs that is produced in nuclear reactors are Np, Am and Cm. The problem of the Np, Am and Cm transmutation with the Pu surpluses is a part of the problem of nuclear power ecological safety and proliferation resistance of the fissile materials.

In the last years, several studies were investigating the use of UO_2 and MOX fuel mixed with MAs in Light Water Reactors (LWRs) and fast reactors to both enhance the economy of the fuel cycle and to enhance the proliferation resistance of fissile materials, and to convert their nuclei to non-radioactive nuclei or to nuclei with shorter decay times [1], [2], [3], [4].

The mentioned Mas play an important role in the physics of the LWRs and fast reactors through their effect on the properties of the fuel cycle. Therefore, all experimental and researches carried out in this field focused on using these actinides in LWRs and fast reactors [1], [2], [3].

Some of the new actinide isotopes resulting from fuel burning in the reactor can undergo the fission process as well. This means that re-fueling the MA has its effect not only on the initial reactivity but also on the duration of the fuel cycle. Therefore, it is very important from my standpoint of view to study the effect of these actinides on the neutronic parameters and fuel cycle in Research Rectors (RRs) having medium power such as the MTR-22MW reactor [4], [5].

The main problem of this research

The radioactive properties and the toxicity of the MAs make them very harmful to human beings and the environment. Therefore, many studies to re-cycle the MAs in the fuel cycle of LWRs and fast reactors have been performed [1], [3], [4], [5], [6]. The results of these studies have showed the following:

- The enrichment with ^{235}U and the required amount of the fuel decrease significantly with increasing the number of fuel assemblies charged with plutonium and MAs,
- Re-cycling of plutonium and MAs together with discharging uranium can reduce the radio-toxicity of discharged heavy metal (HM) waste to become less than that of the loaded uranium, and to reduce the spent fuel for storage and improve the proliferation resistance of the radioactive materials,
- re-cycling MAs and UO_2 fuel together can serve as burnable absorber to reduce the initial excess reactivity.

Since re-cycling RRs by MOX mixed with MAs seems not to be investigated, therefore, it is very important to investigate the re-cycle and effect of the MAs on the neutronic parameters of the RRs. This helps to improve the life of the fuel cycle and re-design the RRs using fuels with MAs and using closed fuel cycle in the future; this leads the burn the MAs resulting from these reactors and remove their risks.

The importance of this research

The major benefit of beginning minor actinide recycling in existing thermal reactors and in the RRs having medium power is that it would remove the

long-lived radiotoxic nuclides from the fission product waste, helps in saving energy and enhancing the proliferation resistance of radioactive materials and serving as a burnable absorber to improve the fuel cycle performance. In addition, the advantage of re-cycling MOX fuel with MAs in RRS is to help in:

- reducing the volume of the spent fuel for storage and enhancing the proliferation resistance, especially the length of the fuel cycle in these reactors is short in comparison with that of LWRs which means burning more plutonium and MAs,
- contributing to extend the spreading of RRs which use MOX fuel with minor actinides or original fuel with some fuel elements of MOX fuel mixed with minor actinides,
- increasing plutonium isotopes utilization,
- reducing the enrichment of the fuel with ^{235}U loading in the reactor core,
- transmuting to less hazardous and possibly more useful forms.
- using a closed fuel cycle for RRs in the future.

The main objective of this paper was discussing the effect of the ^{239}Pu, ^{241}Am and ^{243}Am actinides on the neutronic parameters and the fuel cycle of the MTR-22 MW reactor (The Egyptian Second Research Reactor (ETRR-2) as example). This study was carried out changing only the fuel composition. This means, the dimensions of the fuel material, the Fuel Plate (FP), the Fuel Element (FE), the Reactor Core (RC) or any component of the reactor were not changed.

The MCNP4C code [7] and PECOM system [8] were used to provide comparison between the neutronic characteristics for the proposed core re-fueling by U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides and the initial U_3O_8-Al OFEs core.

2. Methodology

2.1The ETRR-2 reactor

The general characteristics of the ETRR-2 such as: the fuel types, the fuel material, the absorber material and the active zone dimensions are detailed in Table 1 and Table 2 [9], [10], [11], [12].

Parameter	Weight percentage %		
	SFE	FE Type 1	FE Type 2
^{235}U	12.377	6.598	8.398
^{238}U	50.450	26.894	34.230
^{27}Al	25.91	60.504	49.730
^{16}O	11.263	6.004	7.642
Density (g/cm^3)	4.802	3.299	3.655

Table 1: Composition of the fuel in a typical ETRR-2 core.

Table 2: Specifications of the fuel material, fuel element, absorber material, active zone dimensions and water gap between plates of the ETRR-2 core for the U_3O_8-Al OFEs and the U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides.

Parameter	Fuel material	
	U_3O_8-Al original fuel	U_3O_8-Al mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides
Fuel meat	U_3O_8-Al	U_3O_8-Al + ^{239}Pu, ^{241}Am and ^{243}Am
Weight percentage (%)	100	98.2 U_3O_8-Al + 1.3 ^{239}Pu + 0.5 (^{241}Am +^{243}Am)
Enrichment ^{235}U(%)	19.70	10.10

Initial mass of ^{235}U loading in the reactor core (g)	6944.5	6332.956
Saved mass of ^{235}U in the beginning of the load (g)		611.543
Density of fuel (g/cm^3)	See Table 1	4.928

Fuel element				
Number of the fuel materials	29		29	
Number of fuel plates in the fuel material	19		19	
Dimensions of the fuel plate (cm) (length x width x thickness)	80 x 6.40 x 0.07		80 x 6.40 x 0.07	
Absorber material				
Composition	Ag – In - Cd		B_4C	
	Weight percentage (%)		Weight percentage (%)	
	Ag	80	^{10}B	5
	In	15	^{11}B	75
	Cd	5	C	20
Density (g/cm^3)	10.18		2.52	
Active zone dimensions				
Active length (cm)	80		80	
Clad length (cm)	80		80	
External section of fuel element (cm^2)	8×8		8×8	
Section in grid to house the fuel element (cm^2)	x 8.18.1		x 8.18.1	
Plate thickness (cm)	0.15		0.15	
Meat thickness (cm)	0.07		0.07	
Meat width (cm)	6.40		6.20	
Side plate thickness (cm)	0.50		0.50	
Side plate width (cm)	8.00		8.00	
External distance between frames (cm)	8.00		8.00	
Internal distance between frames (cm)	7		7	
Cladding material	Al- 6061		Al- 6061	
Water gap between plates				
of single fuel element (cm)	0.27		0.27	
of different fuel element (cm)	0.39		0.39	

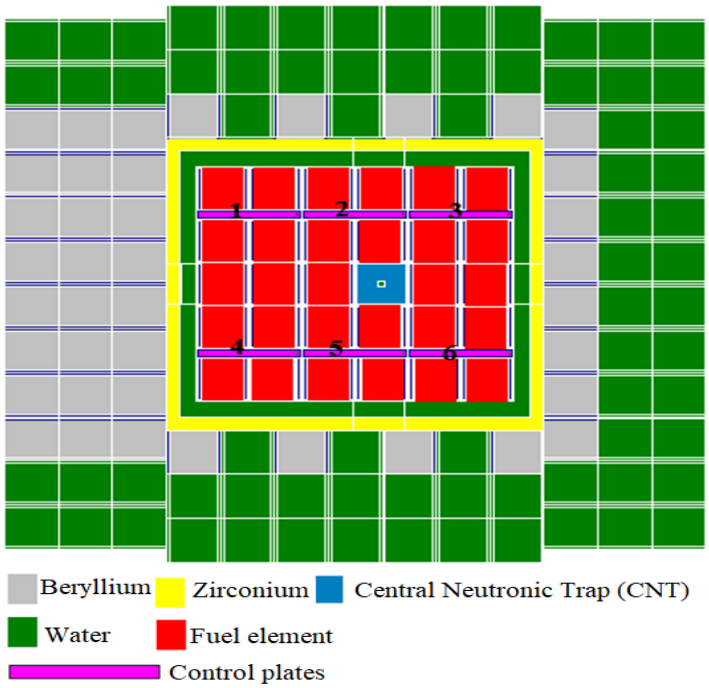


Figure 1: A schematic horizontal cross section of the ETRR-2 core coming

from the MCNP4C code with six control plates.

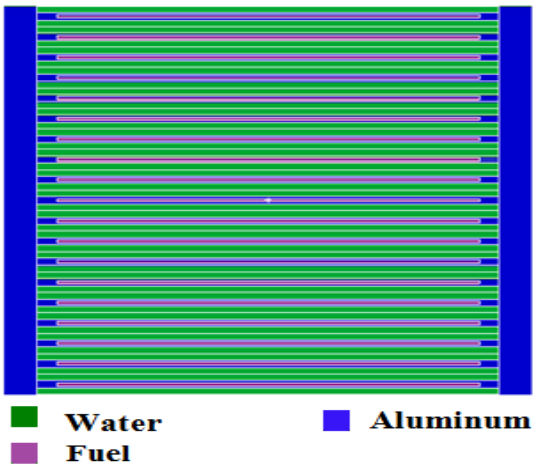


Figure 2: A cross section of the fuel element used in the ETRR-2 by using the MCNP4C code

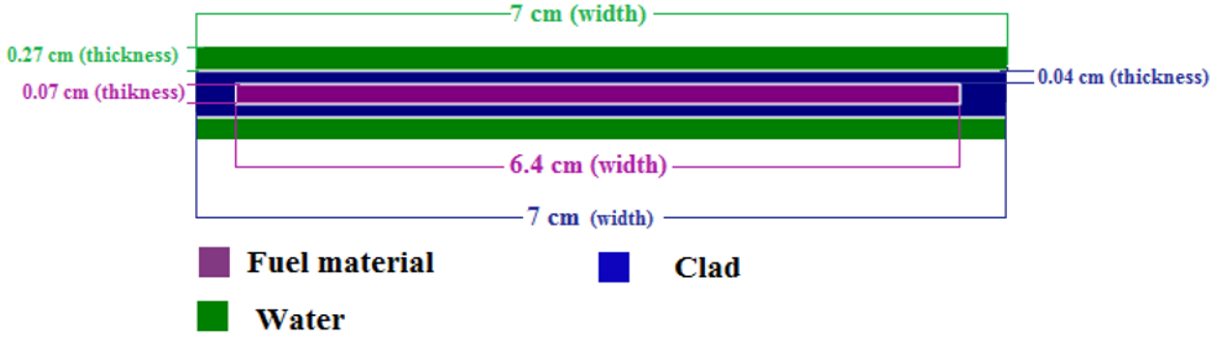


Figure 3: A cross section of the FP by using the MCNP4C code.

2.3 Required conditions for conversion from the U_3O_8-Al OFEs to the U_3O_8-AlOFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides as burnable absorbers.

In assessing the practicability of converting the existing ETRR-2 core to the use of U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides, three factors have to be taken into account:

1. The criticality safety parameters of the fuel should not be lower than those for the current design based on the U_3O_8-Al OFEs,
2. Major modifications to the reactor should not be required, nor should the costs increase,
3. The essential capabilities of the reactor should be conserved requiring the neutron flux in the CNT and the CIB to be conserved,

Therefore, the modifications, which are brought to the ETRR-2 core are related only to fuel material and absorber material in the control plates, where the absorber material Ag-In-Cd alloy was changed into B_4C material for the ETRR-2 core re-fueled by U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides being more effective without changing neither the dimensions nor the sites [13], [14], [15].

The specifications of the fuel material, the fuel element, the absorber material, the active zone dimensions and the water gap between plates of the U_3O_8-Al OFEs and the U_3O_8-Al OFEs mixed with ^{239}Pu, $^{241}Amand$ ^{243}Am actinides are listed Table 2. The weight percentage of the ^{239}Pu ^{241}Am and ^{243}Am actinides used is tabulated in the Table 3 and Table 4 too [16].

Parameter	Weight percentage %
^{238}Pu	0.001
^{239}Pu	95.01
^{240}Pu	4.51
^{241}Pu	0.47
^{242}Pu	0.01

Table 3: Composition of the ^{239}Pu plutonium.

Parameter	Weight percentage %
^{241}Am	60.655
^{243}Am	39.345

Table 4: Weight percentage of the ^{241}Am and ^{243}Am isotopes.

3. Calculation of the power distribution and criticality parameters for the ETRR-2 core refueled by the U_3O_8-Al OFEs and by the U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides.

The MCNP4C code was used to calculate the neutronic and criticality parameters of theETRR-2 core. The following data:

- nuclear data of the fissile and non-fissile materials were taken from ENDF/BVI libraries,
- 400×10^6neutron histories were used to run the code,
- 400 cycles with 50 passive cycles before the active cycles begin,
- initial value of the k_{eff} multiplication factor is 1,
- fuel elements in the ETRR-2 core were used as fission source points,
- fission source locating in the middle of each fuel element,
- *S(α,β)*was used to treat the thermal scattering in beryllium and hydrogen *(See MCNP4C code manual* [7]*).*
- energy range of neutrons was divided to three groups as: <0.625eV for thermal, (0.625eV to 5.53KeV) for epithermal and up to 20 MeV for fast.

were taken to run the input file of the ETRR-2 core by the MCNP4C code and calculate the neutronic and criticality parameters, and the power distributions as well as.

3.1 Criticality parameters

Criticality parameters include the calculation of factors such as:

- The effective multiplication factor,$k_{eff,}$and the corresponding excess core reactivity, ρ_{ex},
- The Shutdown Margin (SM) of the control system,
- The Shutdown Margin with the first control plate is failure (SM – 1),
- The Control Plates Worth (CPsW),
- The Reactivity Safety Factor (RSF). Whereas the calculated value of the RSF was obtained using this relation:

$RSF = CPsW/\rho_{ex}$

Criticality calculations were performed by the KCODE criticality card (See the MCNP4C code manual [7]). The obtained results are listed in Table 5and Table 6.

Table 5: Criticality parameters of the ETRR-2 core re-fueling by the U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides as a burnable absorber actinides and design value for U_3O_8-Al OFEs.

Parameter	Design value for U_3O_8-Al OFEs (pcm) with Ag-In-Cd alloy as absorber material in the control plates	U_3O_8-Al mixed with ^{239}Pu, ^{241}Am and ^{243}Am (pcm) with B_4C alloy as absorber material in the control plates	Differences %	Design value of safety criteria (pcm)
ρ_{ex}at BOC[(1)]	8220	8234.99 ± 6.80	0.18	> 3000
CPsW[(2)]	14120	14213.22 ± 18.95	0.66	> 1000
CPsW[(3)] #1	10390	10630.01 ± 17.70	2.26	>1000
CPsW #2	11030	10791.73 ± 18.87	2.20	>1000
CPsW #3	11050	11074.39 ± 18.25	0.22	>1000
CPsW #4	10810	10656.23 ± 18.84	1.44	>1000
CPsW #5	11330	10881.21 ± 19.04	4.12	>1000
CPsW #6	11290	11294.84 ± 19.34	0.04	>1000

(1) ρ_{ex} at BOC- is the reactivity at Beginning of Cycle,
(2) (CPsW) - is the Control Plates Worth,
(3) CPsW#1 - is the Control Plates Worth without first control plate (See Figure 1)

Table 6: Calculated values of the RSF, SM and SM-1 of the ETRR-2 core re-fueling by the U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides and design value for U_3O_8-Al OFEs.

Statement	Design value for U_3O_8-Al OFEs (pcm) and Ag-In-Cd alloy as absorber material in the control plates	U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am (pcm) and B_4C material as absorber material in the control plates
RSF >1	1.7177	1.7259 ± 0.0032
SM > 3000 pcm	5900	5978.23 ± 15.45
SM -1 > 1000 pcm	2170	2395.02 ± 6.16

3.2 The power distribution parameters

To calculate the power distribution parameters, the Average Thermal, Epithermal and Fast Neutron Fluxes (ATNF, AENF and AFNF)) in the CNT, in the CIB and in the Be beryllium reflector were to be calculated. The calculated values of the ATNF, AENF and AFNF in the CNT, in the CIB and in the Be beryllium reflector with reference values are given in Table 7 for the ETRR-2 core fueled by U_3O_8-Al OFEs and re-fueled by U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides.

Table 7: Calculated values of the neutronic parameters of the ETRR-2 core re-fueling by the U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides and reference values for U_3O_8-Al OFEs.

Parameter	Reference value	Calculated values for U_3O_8-Al original fuel	U_3O_8-Al mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides
ATNF in the CIB (n/cm^2.s)×10^{14}	4.230[(a)]	4.215 ± 0.017	4.276 ± 0.018
AETNF in the CIB (n/cm^2.s)×10^{14}		1.018 ± 0.031	1.037 ± 0.032
AFNF in the CIB (n/cm^2.s)×10^{14}		1.533 ± 0.014	1.563 ± 0.025
ATNF in the CNT (n/cm^2.s) ×10^{14}	2.700[(b)]	2.700 ± 0.007	2.723 ± 0.008
AETNF in the CNT (n/cm^2.s)×10^{14}		0.836 ± 0.008	0.865 ± 0.007
AFNF in the CNT (n/cm^2.s)×10^{14}		1.450 ± 0.007	1.491 ± 0.009

ATNF in the Be reflector (n/cm^2.s) ×10^{14}	1.000[(b)]	0.988 ± 0.014	1.003 ± 0.017
AETNF in the Be reflector (n/cm^2.s)×10^{14}		0.227 ± 0.024	0.232 ± 0.021
AFNF in the Be reflector (n/cm^2.s)×10^{14}		0.297 ± 0.019	0.311 ± 0.025

(a) Reference value was taken from reference (Hussein et al., 2011).

(b) References values were taken from the references (www.etrr2-aea.org.eg/Data Sheet about MTR-22MW.html and Main Core Data of MTR Reactor.html.

The values of the Power Distribution (PD) in the modified ETRR-2 core were calculated to know whether the re-fueled ETRR-2 core by the U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides causes a big change in the values of the peaking power factors compared with the ETRR-2 core fueled by U_3O_8-Al OFEs, and to predict the temperature change resulting from fission in the FEs.

The power peaking factors are the:

- radial P_{rpf} and axial P_{apf} peaking factor of the Hottest Fuel Element (HFE) [17],
- P_{max} maximum and P_{min} minimum power releasing in the FEs,
- P_{avr} average power released in the ETRR-2 core.

The values of the factors P_{rpf}, P_{apf} and the P_{avr} are calculated as:

- P_{rpf} is the ratio between the P_{max} and the P_{avr},
- P_{apf} is the ratio between the maximum power released in the segment of the HFE and the average power released in the HFE [13], [14], [15],
- P_{avr} is the ratio between the calculated value of the power releasing in the reactor core and the number of the FEs.

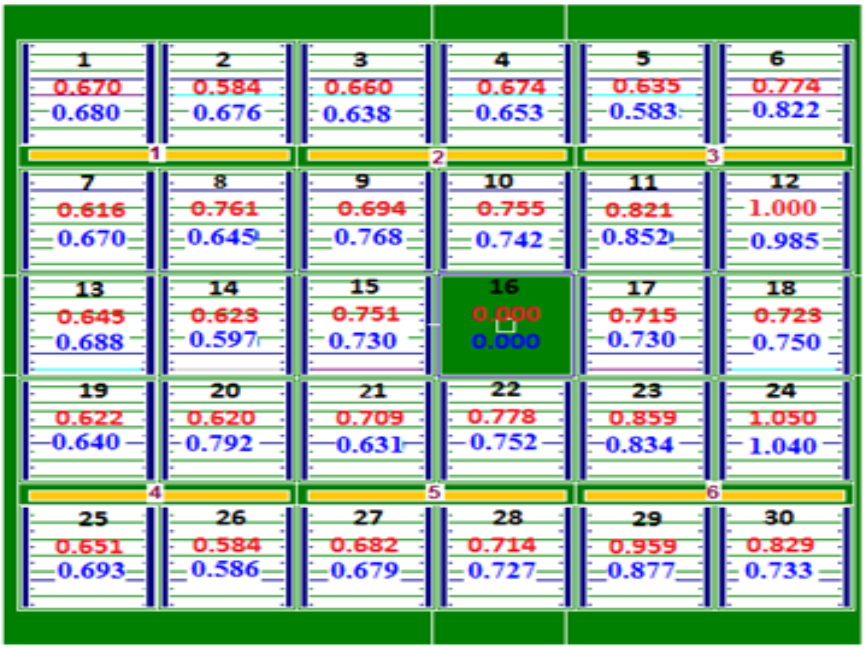
The obtained results of the PD and the power peaking factors are given in Figure 4 and Table 8.

Table 8: Power peaking factors of the ETRR-2 core fueled by U_3O_8-Al OFES and re-fueling by the U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides.

Parameter	U_3O_8-Al original fuel	U_3O_8-Al mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides
Maximum power per element P_{max} (MW/element)	1.050±0.004	1.040 ±0.003
Minimum power per element P_{min} (MW/element)	0.584±0.004	0.576±0.004
Average power per element P_{ave} (MW/element)	0.731±0.003	0.755±0.004
P_{max}/P_{min}	1.798±0.010	1.788±0.012
$P_{rpf} = P_{max}/P_{ave}$	1.432±0.011	1.377±0.039
A_{apf} (MW)	1.428 ±0.010 1.355[(a)]	1.424±0.015
Calculated and reliability value of the power (MW)	21.801±0.004 22[(b)]	21.900±0.004 22[(b)]

(a) Reference value was taken from reference (Mohamed, M.F., 2011.Analysis of Reactivity Accidents in MTR for Various Protection System Parameters and Core Conditions, Thesis, Master of Science. Faculty of Engineering, Alexandria University, Egypt).

(b) Reliability value of the reactor power.



Black color - is the number of the FEs in the ETRR-2 core.
Site 16 - denotes the Central Neutronic Trap (CNT).
Red and blue color - is the calculated values of the PD for the ETRR-2 core refueled by the U_3O_8-Al OFEs and refueling by the U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides, respectively.

Control plates

Figure 4: Calculated values of the PD for the ETRR-2 core refueled by the U_3O_8-Al OFEs and re-fueling by the U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides.

In the calculation the PD in the reactor core and the power peaking factors, and the ATNF, AENF and AFNF in the CNT, in the CIB and in the Be beryllium reflector for the U_3O_8-Al OFEs and the U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Amactinides, the F_4 tally, the FS, the SD and the FM cards in the MCNP4C code were used [13], [14], [15].

5. Study the reactivity as a function of the operation time of the ETRR-2.

The reactivity ρ_{ex} of the ETRR-2 core re-fueling by U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides was studied as a function of the operation time of the reactor for the 10 MW power. This procedure is necessary to safe operational conditions accomplishment in the design of the ETRR-2 core as an initial U_3O_8-Al OFEs. In this case,

to calculate the reactivity ρ_{ex} we used the PECOM system and taken the main actinides and major fission products [13]. The obtained results are plotted on Figure 5 for the U_3O_8-Al OFEs and U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides.

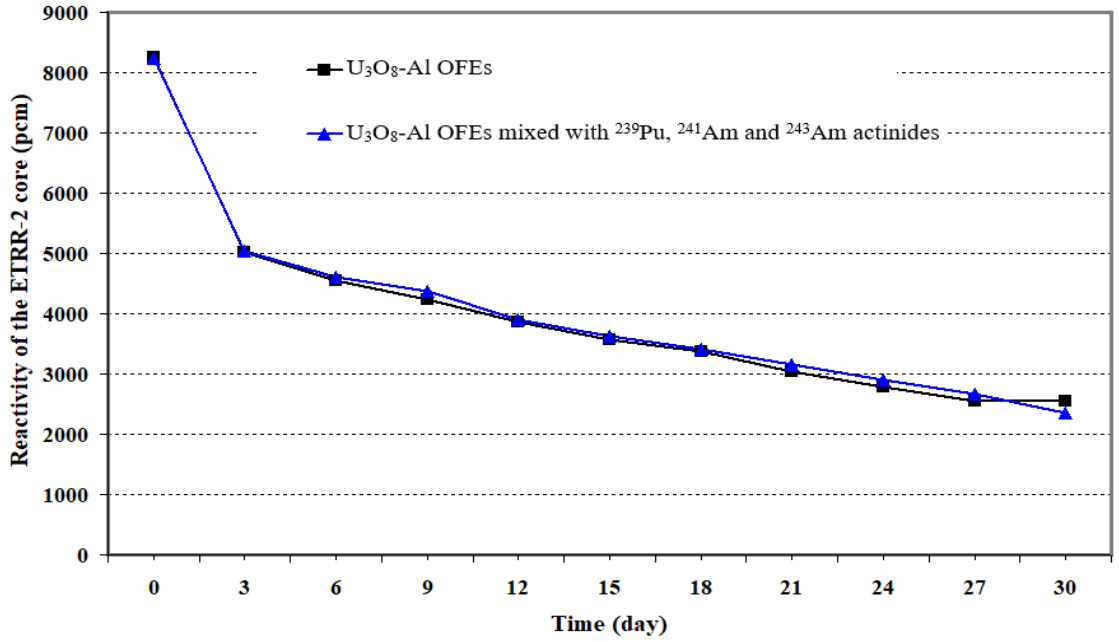


Figure 5: Variation of the reactivity as a function of the operation time of theETRR-2 core refueled by the U_3O_8-Al OFEs and re-fueling by the U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides.

Results and discussion

From Table 5 it results that the maximum difference between the design values of the CPsW for the ETRR-2 core refueled by the U_3O_8-Al OFEs and the ETRR-2 core re-fueled by U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides does not excced 4.12%. This result indicates that the used U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides does not have any negative effect on the criticality safety of the reactor within the conditions given in Table 5.

In the criticality calculations:

- the reactivity ρ_{ex} was calculated from this equation [18]:

$\rho_{ex} = (k_{eff} - 1)/k_{eff}$

- the values of the SM and the SM-1were calculated with the control plates are fully inserted in the ETRR-2 core and the first control plate is failure (See Figure 1), respectively.

- the calculated values of the CPsW were calculated using the following equation:

$CPsW = \rho_{ex} + SM$.

Table 6 shows the calculated value of the RSF, SM and SM-1. Noticeably, from this table the differences between the design values of the RSF, SM and SM-1 for the ETRR-2 core refueled by U_3O_8-Al OFEs and the same parameters forthe ETRR-2 core re-fueled by U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides are 0.48%, 1.30% and 9.39%, respectively. This result enhances that the

use of U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides in the ETRR-2 does not break the safety conditions established in the design of the ETRR-2 (See Table 5, Table 6 and Table 7).

From Table 7 it can be seen also that:

1. the difference between the calculated values of the ATNF, AETNF and AFNF in the CIB and in the CNT, and in the Be reflector are 1.423%, 1.832% and 1.919%, 0.845%, 3.352% and 2.749%, 1.495%, 2.155% and 4.501% respectively. This result emphasizes the fact that re-fueling the ETRR-2 reactor by a U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides will not significantly affect the thermal neutron flux in the CNT and in the CIB, and in the Be reflector. This result leads to say that:

   - re-fueling the ETRR-2 by a U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides will not affect so much the neutronic parameters of the ETRR-2 core,

   - the availability of the scientific applications that were available with U_3O_8-Al OFEs will still be available now with the U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides,

   - The ATNF in the CNT and in the CIB is higher than the 2.0×10^{14} n/cm^{2}s. This value is sufficient to produce the radioisotopes such as: ^{99}Mo ^{14}C, ^{32}S, ^{51}Cr, ^{60}Co, ^{89}Sr, ^{153}Sm, ^{169}Yb, ^{170}Tm, ^{192}Ir [1], [19], [20]. It results from Table 8 that the maximum difference between the calculated values of the parameters P_{max}, P_{min}, P_{ave}, P_{rpf}, A_{apf}, P_{max}/P_{min} is about 3.84% for the ETRR-2 core refueled by the U_3O_8-Al OFEs and re-fueling by the U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides. This result leads to say that re-fueling of the ETRR-2 reactor by the U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides does not create a big change in the power peaking parameters.

Figure 5 shows the reactivity of the ETRR-2 core as a function of the operation time for the U_3O_8-Al OFEs and the U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides. Noticeably, there is a good agreement between these curves. Analysis of these curves shows that the,

1. ^{239}Pu is compensating the reactivity loss that results from the absorption of neutrons by the ^{241}Am and ^{243}Am actinides,
2. ^{242}Am forms as a result of the absorption neutrons by the ^{241}Am (See Figure 6) that has high cross section of fission (2100×10^{-24} cm^2),

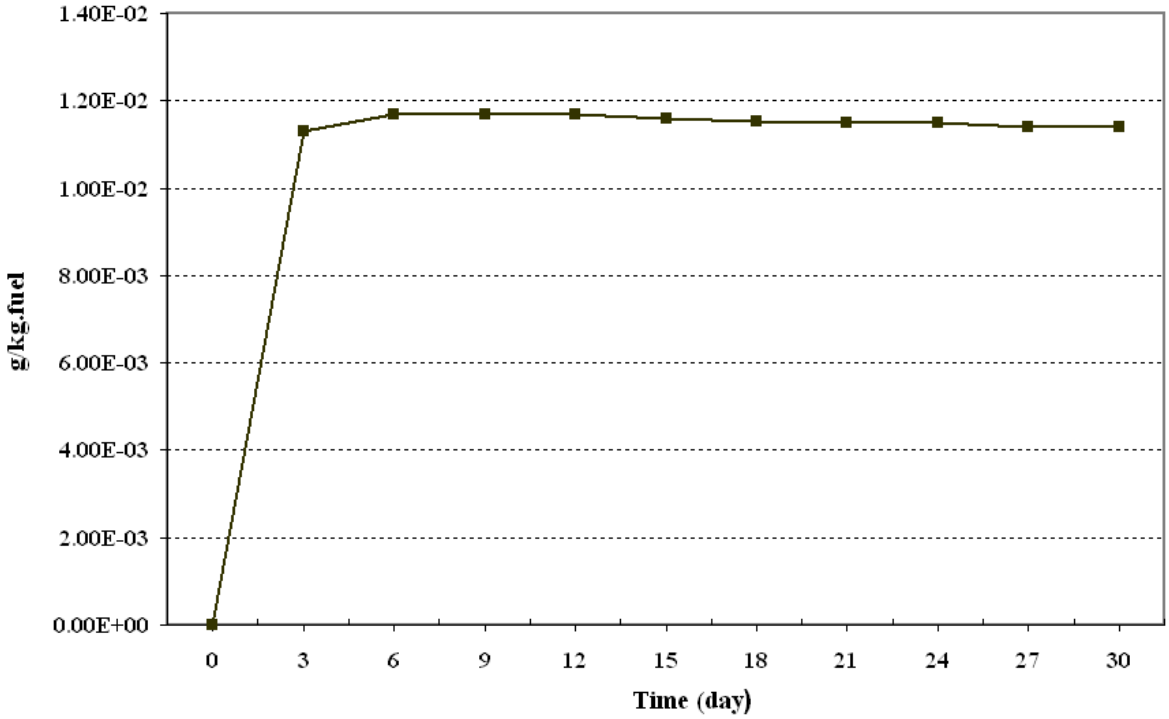


Figure 6: Concentration of the ^{242}Am for the ETRR-2 core re-fueling by the U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides.

3. ^{242}Am increases the fuel burn-up beginning on day15 (See Figure 6) as a result of fissioning the ^{242}Am nuclei. This fact can be used:

- to improve the fuel cycle in RRs,
- to help the conversion from an open to a closed fuel cycle in the future,
- to lower the ^{235}U mass in the fuel or decrease the number of the FEs which are required for a reactor which comes out from enrichment reduction of uranium (See Table 9)
- to compensate the reactivity loss at the end of the fuel cycle.

Table 9: Saved and burning mass of the ^{235}U and ^{239}Pu, ^{241}Am and ^{243}Am per year.

Type	Mass of actinide per year (g)
Saved mass of ^{235}U	8561.616
Burning mass of ^{239}Pu	1187.714
Burning mass of ^{241}Am	220.040
Burning mass of ^{243}Am	96.890

Table 9 shows the saved and burnt mass of the ^{235}U, ^{239}Pu, ^{241}Am and ^{243}Am actinides per year. From this table it can be seen that the burnt mass of the ^{239}Pu, ^{241}Am and ^{243}Am actinides per year is small, but this result is very important because it is open this field to:

- increase researches and enhance the development of a distinguished fuel cycle in RRs by using the minor actinides,
- help in enhancing the proliferation resistance of the radioactive materials.

- prove the possibility of designing RRs with high or medium power with closed fuel cycles in the future,
- burn a bit of the ^{239}Pu in the MTR reactors,
- use of ^{239}Pu, ^{241}Am and ^{243}Am actinides as additional sources of energy,
- contribute in reducing the risks of these actinides in the environment.

Conclusion

The U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides was proposed as a new fuel of the ETRR-2 reactor. Results indicate that the re-fueling of the ETRR-2 reactor by a U_3O_8-Al OFEs mixed with ^{239}Pu, ^{241}Am and ^{243}Am actinides will not have any negative effect on the criticality and neutronic characteristics of the ETRR-2 reactor. Using the ^{239}Pu, ^{241}Am and ^{243}Am actinides leads to reduce the ^{235}U mass loaded in the ETRR-2 core. I hope these results will encourage the researchers in this field to development the fuel cycle in the RRs.

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