Physical Science International Journal

21(3): 1-6, 2019; Article no.PSIJ.48117
ISSN: 2348-0130

Depletion Analysis of the Nigerian Research Reactor Fuel with 19.75% Enriched UO_2 Material

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Authors' contributions

This work was carried out in collaboration among all authors. Author JAR designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors JAR, MYO and DOS managed the analyses of the study. Authors JAR and DOS managed the literature searches. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/PSIJ/2019/v21i330110
Editor(s):
(1) Dr. David G. Yurth, Director, Science & Technology, The Nova Institute of Technology Holladay, Utah, USA.
(2) Dr. Roberto Oscar Aquilano, School of Exact Science, National University of Rosario (UNR), Rosario, Physics Institute (IFIR) (CONICET-UNR), Argentina.
Reviewers:
(1) A. Ayeshamariam, Khadir Mohideen College, India.
(2) Aliyu Bhar Kisabo, Nigeria.
(3) Yaning Zhang, Harbin Institute of Technology, China.
Complete Peer review History: http://www.sdiarticle3.com/review-history/48117

Original Research Article

Received 09 January 2019
Accepted 23 March 2019
Published 28 March 2019

ABSTRACT

The depletion analysis of the Nigerian research reactor fuel with 19.75% enriched UO_2 have been performed using the VENTURE PC code. The matrix exponential method was selected in this work to perform the depletion analysis. The volume fraction of the materials in this mixture was calculated and multiplied by their respective atom densities to obtain the effective atom density of the nuclide in the water, Aluminium mix region of the fuel cell model. The plot of the variation of *k* infinity versus hydrogen to Uranium ratio was generated using Matlab programming language for processing of the computer code result. This shows that as the ratio of hydrogen to uranium in the core of the reactor is increased, the reactivity also increases by gradually increasing the fuel cell radii till it gets to the peak of 0.6193. Any further increment in the radius of the fuel cell radii, the reactivity of the reactor decreases as the hydrogen to uranium ratio increases.

Keywords: Depletion; reactor; uranium; reactivity.

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1. INTRODUCTION

It has been more than three decade since the first nuclear reactor achieved a critical fission chain reaction. Since that time, an extensive worldwide effort has been directed towards nuclear reactor research and development in an attempt to harness the enormous vigour contained within the atomic nucleus for peaceful application. Nuclear reactors have evolved from an embryonic research tool into the mammoth electrical generating building block that drive century of central-station power industrial plant around the world today [1].

The current shortage of fissile fuels has made it quite obvious that nuclear fission reactor will play a dominant role in meeting man's energy requirements for many years to come. The dominant function played via nuclear fission reactors in the generation of electricity can be predicted to proceed well into the next century. Nuclear energy will signify the solely doable choice to fissile-fueled plant for most nations.

Fuel depletion analysis has to do with the prediction of the long-term changes in reactor fuel composition caused by exposure to neutron flux during reactor operation. Such changes have a vital bearing on the operating life of a reactor, as well as on its balance and control. The shift in the core power distribution that accompanies fuel burnup does not result in the exceeding of core thermal limitations. Sufficient extra reactivity ought to be supplied in the fresh core loading to acquire the desired fuel exposure which is consistent with safety limitations.

Analysis of core composition is a necessity in order to optimize fuel exposure to achieve minimal power costs as well as determine the cost of discharged fuel, since the fuel cost over the operating lifetime of the reactor can exceed those of the capital cost of the plant itself.

Uranium dioxide (UO2), a ceramic fuel is at present the most in many instances used nuclear fuel for both research and power reactors. Uranium dioxide material is the fuel of preference for most reactors due to its excessive melting point (2800°C), excessive neutron utilization, first-rate irradiation stability, exceptional corrosion resistance in conventional coolants, precise fission product retention, no segment change up to the melting point, compatibility with cladding (Zircaloy and stainless steel), ease of fabrication, and excessive unique power and energy per unit size of fuel pin [2].

During reactor operation, the fuel material in the core of the system deplete with time due to consumption for fission/absorption reaction inside the reactor system. For the existing Nigeria Research Reactor-1 (NIRR-1), burnup calculations can be used to predict long- term changes in the isotopic composition of its fuel material, brought about by exposure to neutrons of different flux level, leading to fuel irradiation in the core of the system in the course of reactor operation.

The existing NIRR-1 system is fueled with UAl4-Al enriched to 90.2% U235 and the end result from a range of depletion calculations has proven that the system can be operated with a burnup of less than 1% for a length of 10 years [3]. It is designed on the whole to serve as a neutron source. The core is a cylindrical fuel assembly, approximately containing 347 fuel elements [4].

The fuel element is 248 mm in size with the active size being 230 mm. The diameter of the fuel "meat" is 4.3 mm and the U235 loading in every fuel element is about 2.88 grams [5]. The current Highly Enriched Uranium (HEU) Nigeria Research Reactor-1 (NIRR-1) has a tank-in-pool structural configuration and a nominal thermal power rating of 31.1 kW [1]. The current core of the reactor is a 230 x 230 mm square cylinder and fueled by using U-Al4 enriched to 90.2% [6]. The computer code selected to perform these depletion/burnup calculations for the current NIRR-1 core is the VENTURE PC [7]. The present NIRR-1 system is fuelled with UAl_4-Al enriched to 90.2% U235.

In this work, Depletion analysis was performed in order to determine variation of *k* infinity versus hydrogen to Uranium ratio of the designed reactor system when fueled with the proposed UO_2 material enriched to 19.75% U235.

2. MATERIALS AND METHODS

The NIRR-1 contains 347 fuel elements and is arranged in ten concentric circles. Between these fuel pins are radial pitch which varies from one concentric circle to the other.

The NIRR-1 also consist of 4 tie rods and 3 dummy pin. The variation in the radial pitch between the fuel pins as well as the tie rods and dummy pins in the core was a problem during the selection of a single pin from any circle to calculate the volume of the moderator per pin in order to develop the fuel cell model.

Supposing there are no dummy pin or tie rods in the core of the reactor, then we calculate the entire volume of the core per pin using the 347 fuel pins. The volume of water region in the fuel cell is a mixture of both the volume of moderator, tie rods and dummy pins.

The VENTURE module and the BURNER code module are two modules of VENTURE PC code system that are used to perform depletion analysis of the NIRR-1 core.

While the venture module performs the neutronic part of the calculation, the burner code module performs the depletion calculation.

The active material in the reactor fuel pin has a diameter of about 4.3 mm and 230 mm long. It is surrounded with aluminum alloy of about 0.6 mm thick called the fuel clad.

The matrix exponential method which has been selected in this work to perform the depletion analysis is one of the several methods that can be used by burner code to solve burnup equation. This matrix exponential method result from the need to expand exponential in the first order differential equation solution associated with burnup as recommended in VENTURE Manual, 2002 [8].

The volume fraction of the materials in this mixture was calculated and multiplied by their respective atom densities to obtain the effective atom density of the nuclide in the water, Al mix region of the fuel cell model.

$$Total\ vol.of\ fuel\ region\ in\ the\ core = vol.of\ core - guide\ tube\ vol \quad (1)$$

$$\pi r^2 - \pi r^2 = \pi(11.55)^2 - \pi(0.6)^2 = 418.1336 cm^2$$

$$total\ vol\ of\ core\ per\ fuel\ pin = \frac{418.1336}{347} = 1.2050 cm^2$$

$$Thus, fuel\ cell\ outer\ radii = \sqrt{\frac{toatl\ vol\ of\ core\ per\ fuel\ pin}{\pi}}$$

$$= \sqrt{\frac{1.2050 cm^2}{\pi}}$$

$$= 0.6193 cm$$

The total number of Hydrogen atoms in each of the eleven cases was computed; firstly the moderator volume associated with each of the fuel cell outer radius was calculated by subtracting the fuel plus clad volume from the fuel cell volume.

The value of the moderator volume was multiplied by the hydrogen region atom density to obtain the total number of hydrogen atoms in each of the eleven cases.

The total number of uranium atoms in the fuel cell was also obtained by first determining the volume of the active fuel in each of the fuel radii.

The uranium in the HEU fuel is enriched to 19.75% with each fuel pin containing 2.88 g of U235. The height and diameter of the active fuel materials are 23.0 cm and 0.43 cm respective.

Since the mass density, ρ, of a material is known, then the material atom density, N, can be calculated using equation 2

$$N = \frac{(\rho g/cm^3)(N_A atoms/gmole)}{M g/gmole} \quad (2)$$

Since there are several isotopes present with known abundances we have:

$$N_i = \frac{\gamma_i \rho N_A}{M} \quad (3)$$

The chemical composition of a mixture of element in terms of weight percent is expressed as:

$$N_i = \frac{\rho_i N_A}{M_i} = \frac{W_i \rho N_A}{M_i} \quad (4)$$

The molecular weight of the mixture was calculated in order to perform density computations

For any components given in fraction, equation 5 applies.

$$\therefore \frac{1}{M} = \sum \frac{W_i}{M_i} \quad (5)$$

The density of Uranium dioxide (UO_2) is 10.6 g/cm^3 and the weight percent of U235 is 19.75%

The molecular weight of U and UO_2 was determined by

$$\frac{1}{M_u} = \sum \frac{W_i}{M_i} \quad (6)$$

The Uranium atom density was calculated by summing the atom density of U235 and U238 as shown in the equation below

$$N_u = N_{u235} + N_{u238} \quad (7)$$

The total number of Uranium atoms in the fuel cell is then calculated by multiplying the volume of the active fuel by the Uranium atom density as shown in equation 8

$$U - atom = N_u \times volume\ of\ active\ fuel \quad (8)$$

The homogenized atom density for U235, U238 and O were calculated by simply multiplying the region atom density by the region volume fraction.

The volume fraction was calculated first by calculating the volume of each zones in the system and then divide each value by the total volume of the equivalent fuel cell.

3. RESULTS AND DISCUSSION

The calculation was performed using the highly sophisticated code VENTURE PC. The plot of the variation of k infinity versus hydrogen to Uranium ratio was generated using Matlab programming language for processing of the computer code result.

Fig. 1 shows the result of the variation in K_∞versus hydrogen to uranium ratio for the LEU core. As the ratio of hydrogen to uranium in the core of the reactor is increased, the reactivity also increases by gradually increasing the fuel cell radii till it gets to the peak (reference level) of 0.6193. Any further increment in the radius of the fuel cell radii, the reactivity of the reactor decreases as the hydrogen to uranium ratio increases. The position of the peak (reference level) in the figure predicted an over moderated system for the core and not the under moderated system as reported in most literature materials.

Table 1. The value of the total number of hydrogen atom in each fuel cell radius

S/No	Fuel cell radii (cm)	Moderator volume (cm^2)	Hydrogen region atom density. (atom/b-cm)	H-atom (Atom/b-cm^2)
1.	0.298	0.9526		6.3253e-2
2.	0.306	1.3018		8.6440e-2
3.	0.324	2.1216		14.0874e-2
4.	0.357	3.7460	6.640e-2	24.8734e-2
5.	0.408	6.5663		43.6002e-2
6.	0.459	9.7625		64.8230e-2
7.	0.510	13.3348		88.5431e-2
8.	0.561	17.2831		114.7598e-2
9.	0.6192	22.2483		147.7287e-2
10.	0.714	31.3843		208.3918e-2
11.	0.816	42.6652		283.2969e-2

Table 2. Table for the total Uranium atom density in the fuel cell

S/No.	Fuel cell radii (cm)	Volume of fuel cell (cm^2)	Uranium region atom density. (atom/b-cm)	U- Atoms (atom/b-cm^2)
1.	0.298	6.4193	2.36267e-2	7.8946e-2
2.	0.306	6.7685		
3.	0.324	7.5883		
4.	0.357	9.2127		
5.	0.408	12.0330		
6.	0.459	15.2292		
7.	0.510	18.8015		
8.	0.561	22.7498		
9.	0.6192	27.7150		
10.	0.714	36.8510		
11.	0.816	48.1319		

Table 3. Table for the average homogenized atom density for the fuel cell

Metal name	f_i	Nuclides	N_{ij}	$N_{ij}f_i$	N_{iz}
Fuel	0.0694	U235	4.727e-3	3.2803e-4	3.2803e-4
		U238	1.896e-2	1.3117e-4	1.3117e-4
Clad	0.0442	Zr-40090	2.165e-2	9.5693e-4	
		Zr-40091	4.721e-3	2.0867e-4	
		Zr-40092	7.217e-3	3.1899e-4	1.8599e-5
		Zr-40094	7.314e-3	3.2328e-4	
		Zr-40096	1.178e-3	5.2068e-5	
Moderator	0.8864	H1	6.640e-2	5.8857e-2	5.8857e-2
		O16	3.320e-2	2.9428e-2	4.1998e-2

Table 4. Table for atom density of various nuclides present in cladding material (Zirc4alloy)

Matl name	Nuclide name	Nuclide ID	M_i	$W_i(^{W}/_{O})$	$N_{mix}\ (atoms/b-cm)$
Zircaloy-4	Zirconium	40000	91.224	98.23	4.208e-2
	Tin	50000	118.71	1.45	5.377e-4
	Iron	26000	55.845	0.21	1.780e-4
	Chromium	24000	51.996	0.10	8.339e-5
	Hafnium	72000	178.49	0.01	4.491e-6

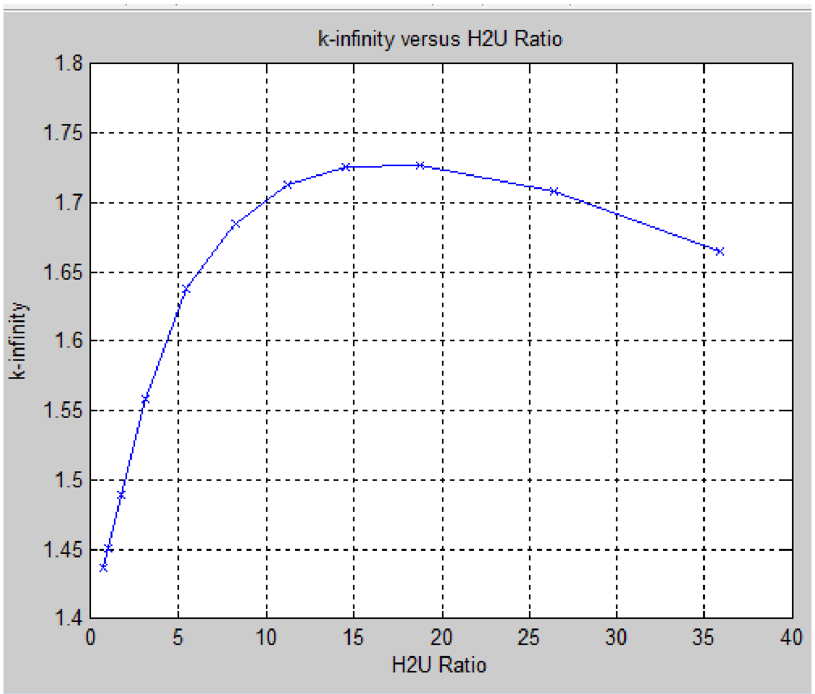

Fig. 1. The variation in *k*-infinity versus hydrogen to uranium ratio for the LEU core

4. CONCLUSION

The Nigeria Research Reactor -1(NIRR-1) is one of the reactor around the world that require conversion from HEU to LEU fuel. It is a compact low power nuclear research reactor designed by China Institute of Atomic Energy. Several analyses have been going on around the world on core conversion studies of this type of research reactor.

This work contain useful information about the process for the preparation of input for depletion calculation for the Nigeria Research Reactor (NIRR-1) using VENTURE PC code. Most of the data generated in this work can be very useful in explaining the behavior of the proposed 19.75% fueled LEU core for NIRR-1.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sdiarticle3.com/review-history/48117