Arab Journal of Nuclear Sciences and Applications

Web site: ajnsa.journals.ekb.eg

ISSN 1110-0451

(E S N S A)

Improving Neutronic Performance of Floating Nuclear Reactor Using Different Fuel Cycles Alternatives

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ARTICLE INFO

Article history:

Received: 9th Dec. 2024

Accepted: 8th Jan. 2025

Available online: 1st Mar. 2025

Keywords:

KLT-40S;

Floating Reactor;

Nuclear Power Propulsion;

Uranium Nitride;

Thorium Fuel.

ABSTRACT

KLT-40S nuclear reactor is a small modular floating nuclear power plant which is used to supply electricity to isolated zones or installed in submarine/icebreakers. Increasing fuel life time in the reactor core is a premium target to improve the efficiency and enhance the operation time of the ships between refueling. Five different types of fuel are tested on an assembly of KLT-40S reactor. These types are: Typical UO_2 fuel dispersed in silumin alloy, uranium nitride fuel, uranium nitride mixed with ZrO2, thorium mixed with ^{235}U and thorium mixed with ^{233}U. The fuel enrichment and the ratio of Silumin alloy is fixed among all types of fuel. Characteristics and neutronic performance of all fuel types are analyzed. The results indicate that replacement of UO_2 fuel by uranium nitride and thorium mixed with ^{233}U increases the fuel cycle length by 24 % and 17 % respectively. Uranium nitride has the highest fissile plutonium breeding, thorium fuel supports proliferation resistance with low minor actinides production.

1- INTRODUCTION

KLT-40S is a Russian design, small modular and floating nuclear power plant. The power of the reactor is 150 MWth or 35 MWe. The reactor core design is based on ship technologies and uses fuel with uranium-235 enrichment of 18.6 %. The reactor is usually installed on a nuclear submarine or icebreaker. The reactor is also used in remote or isolated areas. It supplies electricity, heat and water desalination. Unlike land based reactors in which refueling take place every 18 months, refueling takes place once every 3 years [1,2,3].

Fuel residence time (fuel cycle length) is the time between two successive refueling during reactor operation. It is a crucial and economic parameter for small modular reactor especially KLT-40S reactor. Cycle length depends on multiplication factor of the core and breeding capability during fuel burnup, to improve cycle length, these parameters should be maximized. Accident tolerant fuels (ATF) are a set of new technologies that have the potential to resist abnormal situations by offering better performance during normal operation and accident conditions, and according to this definition, ATF last longer times in the reactor and enhance plant safety [4].

Generation IV International Forum and many scientific institutions adopt new fuel types such as Uranium Nitride and thorium fuels. Nitride fuel has a better thermal conductivity that increases with temperature rises which enhances the safety margins during operation. Uranium Nitride (UN) has a higher density (more fissile content) and good chemical compatibility with most potential cladding materials, as well as irradiation stability. Thorium reserves in the earth is 3 to 4 times more than uranium. thorium can generate U-233 isotope that enhances breeding with low minor actinides production [4,5].

As a review on the previous reactor research; Zhou and et.al. [6] Studied the effect of KLT-40S fuel assembly design on Burnup characteristics, they used different enrichment distributions (power flatting designs) to reduce the assembly power distribution below 1.11 throughout the lifetime. Fajri and et. al. [7] analyzed the core neutronic parameters (such as fuel cycle length and reactivity feedback coefficients) to conform the core feasibility from operational and inherent safety characteristics. IAEA report [1] provided a historical overview for KLT 40S nuclear reactors, main data, characteristics and descriptions for reactor systems.

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DOI: 10.21608/ajnsa.2025.342927.1865

Baybakov et al. [8] presented a method for evaluating the KLT-40S reactor multiplication factor and breeding ratio at operating conditions for different types of fuel compositions. Baatar and Glaskov [9] found that addition of neptunium as burnable poisons in the fuel compositions can significantly increase fuel burn-up in KLT-40S reactor and LWR in general. Beliavskii et al. [10] studied parameters that affect fuel cycle length in the core of KLT 40S by examining four types of fuel compositions, the study explained the methodology used in the analysis. Lee et al. [11] performed a general reviews for all types of floating nuclear reactors. The study includes the general arrangement, design parameters and safety features. Beliavskii et al.[12] performed a study for four types of fuel compositions, the study includes fuel cycle length and burnup characteristics of the fuel composition, the study concludes that (Th + ^{233}U) have higher fuel cycle length and better burnup characteristics.

In the present research, different fuel types are proposed for the reactor, namely Uranium Nitride (UN), Uranium Nitride mixed with Zirconium Oxide ($UN+ZrO_2$), thorium mixed with ^{235}U ($Th+^{235}U$), thorium mixed with ^{233}U ($Th+^{233}U$), in addition to the typical UO_2 fuel with enrichment 18.6 %. All fuel types are dispersed in Silumin alloy. MCNPX computer code is used to model an assembly of the reactor. The results are obtained to optimize and improve neutronic parameters of the reactor core. The obtained results includes reactor multiplication factor, cycle length, fuel burnup, power and flux distribution.

In the present study, section 2 contains material and reactor data, section III presents computational method , section IV contains the output results and analysis. section V contains conclusion and the references are given at the end of the paper.

2- MATERIALS AND REACTOR DATA

The KLT-40S reactor core consists of 121 fuel assemblies. Each fuel assembly comprises 102 main fuel rods in addition to 18 rods mixed with burnable poison, main rods have radius of 0.31 cm, clad thickness of 0.5 mm, active rod height 120.0 cm. Fuel assembly pitch is 10 cm with peripheral wrapper thickness 0.1 cm. The fuel rods are distributed in the assembly in a triangular lattice with fuel rod pitch of 0.995 cm. Dispersed fuel consists of fuel oxide particles and an inert silumin matrix (silumin is an alloy that comprises 89.1 wt% of aluminum and 10 wt% of silicon in addition to impurities [7]. Silumin alloy has better thermal and chemical properties (~180 W/(m•K) [6 ,7].

For Burnable poisons, there are 12 peripheral gadolinia based burnable poison with an external radius 0.31 cm and 6 central burnable poison rods with external radius 0.23 cm. A cylindrical displacer with a radius 1.3 cm and a thickness of 0.5 mm is situated in the center of each fuel assembly and control rods movement inside this displacer space.

The pressure of the primary circuit 12.7 MPa, Coolant inlet/Outlet temperature is 280 ºC/316 ºC. Nuclear fuel average temperature is 370 ºC, cladding average temperature 350 ºC. Cladding material is E635 alloy (Zr + 1 % Nb). Fuel enrichment 18.6 %. Table (1) illustrates the uranium silumin alloy for fuel rods and fuel mixed with burnable poisons rods. Figure (1) illustrates KLT-40S reactor installed on a ship for providing electricity, district heating and water declination.

Table (1): Composition of fuel rod and burnable poison rods [7]

	Density g/cm^3	Silumin alloy fraction	
		Fuel rod	Burnable poisons rod
UO_2	10.96	0.436	0.371
Silumin alloy	3	0.564	0.481
Gd_2O_3	7.07	0.0	0.148

3- III- Computational Procedure:

Five different fuel types are considered in the analysis and the neutronic performance for the assembly is evaluated and compared as follows:

Case A: UO_2 fuel mixed with Silumin alloy with ratio 0.436 and 0.564 for UO_2 and silumin alloy respectively and burnable poison rods consists of UO_2 , Silumin alloy and Gd_2O_3 with fraction 0.371 , 0.481 and 0.148 respectively [Table 1].

Case B: Uranium Nitride (UN) fuel mixed with Silumin alloy with ratio 0.436 and 0.564 for UN and silumin alloy respectively and burnable poison rods consists of UN, Silumin alloy and Gd_2O_3 with fraction 0.371 , 0.481 and 0.148 respectively.

Case C: Similar to case B, but UN is mixed with ZrO_2 with the ratio 90 % and 10 % for UN and ZrO_2 respectively ZrO_2 is mixed with UN to reduce the interaction of UN with water at higher temperatures.

Case D: $^{232}Th + ^{235}U$ is used with the same fuel /alloy ratio like case A.(Thorium concentration equal the same amount as ^{238}U)

Case E: $^{232}Th + ^{233}U$ is used with the same fuel /alloy ratio like case A. (Thorium concentration equal the same amount as ^{238}U)

MCNPX computer code [Hendricks 2007] which is based on Monte Carlo method is used to model the geometry and composition of KLT-40S assembly as indicated in Figure (2). Burnup cards are employed in the input model to represent fuel burnup and time dependent parameters of the assembly. Power per assembly equals 1.23 Mw. Reflective boundary conditions are implemented to outer surfaces of the assembly to consider neutron leakage and interactions with neighboring assemblies inside the reactor core.

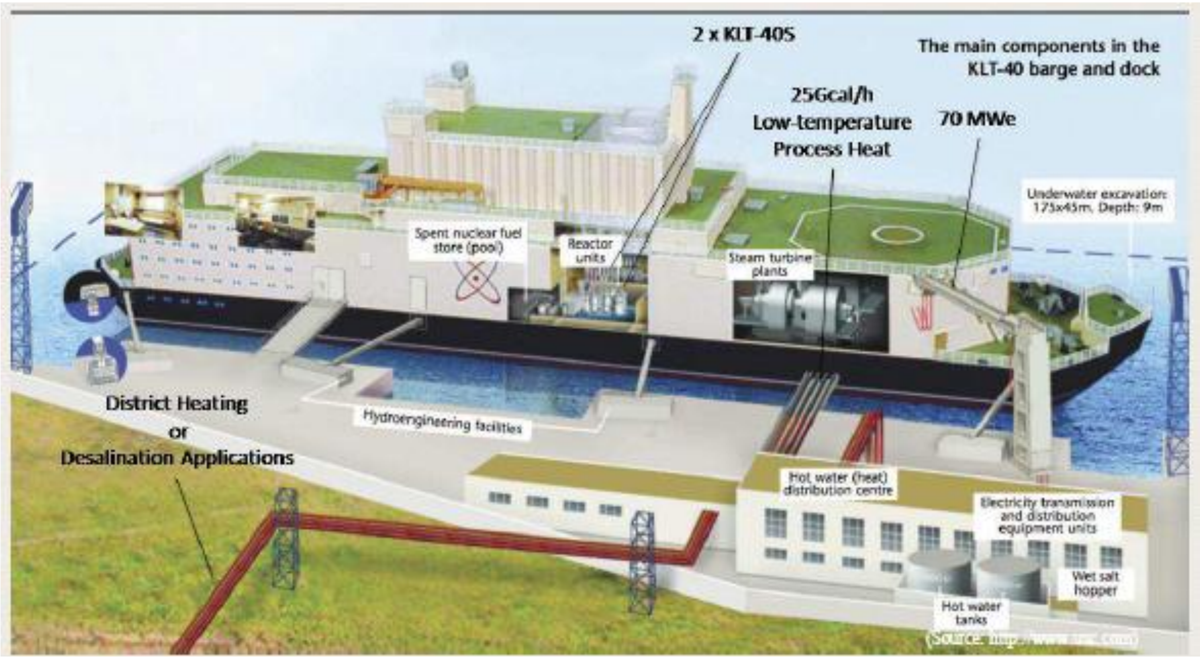

Fig. (1): KLT-40S reactor in different applications [14]

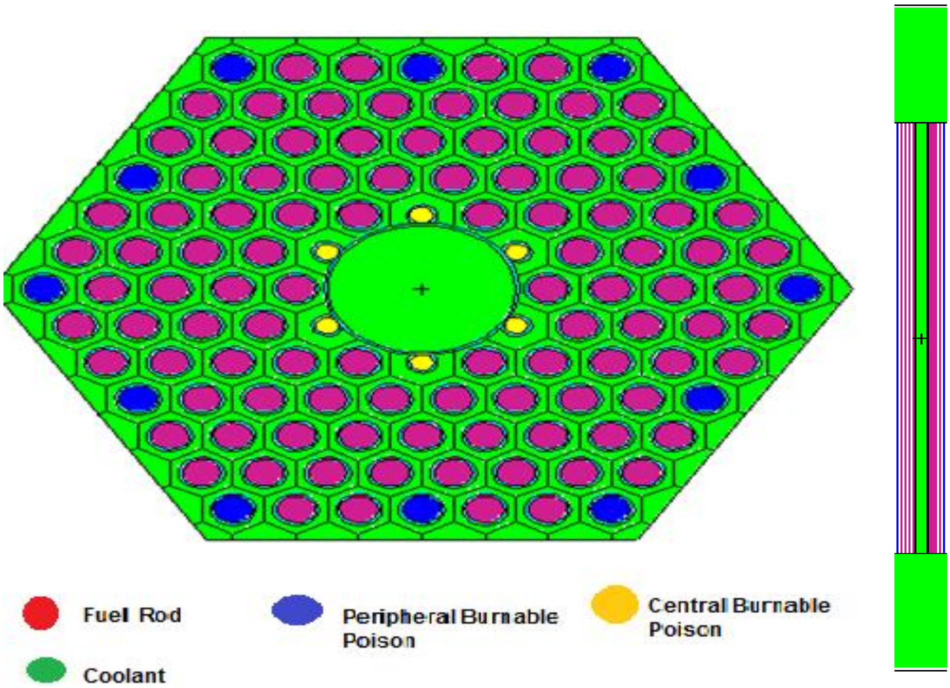

Fig. (2): MCNPX model for KLT-40S assembly

4- IV- RESULTS AND DISCUSSIONS

Core multiplication factor and Reactivity

Figure (3) illustrates multiplication factor for the assembly for 5 different types of fuel versus burnup time (days). Five different cases A, B, C, D and E which are described in the previous section (with burnable poison considered in all cases). The initial multiplication factor is 1.15915 , 1.19461 , 1.15998 , 1.15429 , and 1.46782 for cases A , B , C, D , and E respectively. Case E with fuel (Th +U-233) resulted in a higher K_{inf} with initial value of 1.46782. For all cases, K_{inf} starts to increase due to burn out of burnable poisons up to the time at which effect of burnable poisons are negligible in the assembly, and then multiplication factor starts to decrease again due to fuel consumption and burn up. The cycle length for cases A, B, C, D and E are 1450 day, 1800 day, 1550, 1400, and 1700 days respectively. The second case (B) with UN fuel is the highest cycle length although case E (Th + U-233) has a higher multiplication factor , because uranium nitride UN has a higher uranium inventory and produces more secondary fissile isotopes (Plutonium-239) during burn up which contributes to increasing the cycle length of the fuel . Case E with fuel ^{233}U mixed with thorium has a higher multiplication factor because the ratio of fission to capture cross section for ^{233}U is 0.92 and for ^{235}U is 0.84 , so ^{233}U has a higher fission rate at the beginning of the cycle.

To investigate the behavior of multiplication factor for the assembly of different reactor fuels gadolinium concentration, fission rate and absorption rate should be calculated and analysed. Figure (4) illustrate average gadolinium isotopes ^{155}Gd and ^{157}Gd concentrations (atom/barn.cm) versus burnup time (day) for the first case A (UO_2 fuel) . The absorption cross sections (σ_a) are 61,000 barn and 254,000 barn respectively. The results indicates that ^{155}Gd and ^{157}Gd concentrations at approximately 550 days drops to below 1/1000 from the initial concentration, it is the same time at which K_{inff} at Figure (3) (for UO_2 case) starts to turn to the peak and then decrease (burnable poisons became negligible and totally burns out from the assembly).

Figure (5) shows the fission rate (fissions/s) versus operation time (day) for the assembly, the results show that the fission rate per assembly per second increases for all cases because the power is constant during burnup so fission rate should increase to compensate for the decreases of fissile isotopes during burn up.. Case E for (Th+U233) fuel shows a superior fission rate because the fission to capture rate for ^{233}U is higher (0.92) than that for ^{235}U. This also explains the higher value of K_{inf} for the assembly at the beginning of fuel burnup at Figure (3).

Figure (6) illustrates capture rate (absorptions/s) versus operation time (day) for the assembly. The results show that Case E (Th+U233) fuel has the lowest capture rate at the beginning of the cycle which means more neutrons are allocated to fission in case E than other cases which tend to peak K_{inf} at the beginning of the cycle.

Figure (7) illustrates the multiplication factor (K_{inf}) for the assembly versus burnup time (day) for typical UO_2 case dispersed in silumin alloy with and without burnable poisons. The multiplication factor is 1.15915 and 1.5915 with and without burnable poison respectively. The difference $\Delta K = 0.43235$ represents the worth of burnable poison rods (both outer and inner rods) burnable poisons inhibit the initial reactivity of the assembly due to neutron absorptions by gadolinium. After approximately 500 days burnable poison burns out and the two cases approach each other and became approximately equal. The cycle length for this case equals 1450 days (at which the multiplication factor equals 1.0) The effect of burnable poisons is similar for all cases.

Isotopic Transformation

Figure (8) illustrates fissile U-235 mass (gm) versus burnup time for the fuel (day). The same different cases A, B, C, and D. Cases A , D have equal mass of ^{235}U. Case B, Uranium nitride (UN) is higher density (13.5 gm/cm^3) than UO_2 (10.2 gm/cm^3) , also case C (UN +ZrO_2) which consists of 90 % UN. All fissile isotopes ^{235}U (cases A, B, C , D) decreases with time due to fuel burnup and consumption. The ratio of fissile U-235 burnt to the initial mass at the end of the fuel cycle are 0.82 , 0.78 , 0.78 and 0.83 for cases A, B , C, and D respectively. The fuel cycle for each type is given at Figure (3). .

Figure (9) provides a comparison between total mass of fissile isotopes produced (gm) versus burnup time (day). Total mass of fissile isotopes is the calculation of the masses of ^{239}Pu+^{241}Pu produced as a result of absorption of ^{238}U by neutrons. The results indicate that Case B (UN fuel) has higher masses of fissile plutonium isotopes. While cases D and E which contain thorium have the lowest plutonium fissile rate. The results indicates that thorium satisfies proliferation resistance.

Figure (10) shows a comparison between U-233 (gm) produced during fuel operation (day) for cases D and E. For case D (Th+^{235}U) ^{233}U is produced from thorium and increases with time because it is a secondary fissile isotope, ^{235}U is the main fissile isotopes. However, in case E (fuel Th +^{233}U) ^{233}U is produced from thorium and consumed again to produce the power. U-233 is consumed due to neutron fission and absorption , while also produced due to conversion of thorium to U-233. The production cycle of ^{233}U is illustrated below, thorium interact with neutrons to form ^{233}Th which decays to Protactinium and then decays to ^{233}U

$$^{232}Th(n,\gamma)^{233}Th \rightarrow {}^{233}Pa \rightarrow {}^{233}U$$

Figure (11) illustrates Xenon-135 (atom/barn.cm) versus operation time (day). The results show that xenon-135 increases from zero at start up (t=0.0) and increases at early start up times and then starts to decreases again because xenon is proportional to fissile isotopes concentration which always decreases with operation time due to fissile isotopes consumptions with time. UN has a higher xenon concentration because it has a higher fissile content.

Figure (12) illustrates Neptonium-237 (atom/barn.cm) versus operation time (day). Np-237 increases with time for all cases. Cases B and C coincidence with each other. Cases E (Th+U233) has the lowest Np-237 concentration because thorium fuel supports proliferation resistance and produces less actinides than uranium fuels. Np-237 is indicator of the production of higher actinides.

Kinetic Parameters and Safety Coefficient:

Reactor Kinetics parameters and temperature reactivity coefficients are of utmost importance in reactor operation and accident analysis. Table (2) illustrates comparisons of five safety parameters for all fuel types at beginning of cycle (BOC), namely Prompt neutron life time (Λ), delayed neutron fraction (β), fuel and moderator temperature coefficient of reactivity and void coefficient.

Prompt neutron life time (Λ) is calculated as a built-in parameter in MCNPX code, the results are comparable to each others and their range for all types is 15.7 to 18.21 μs. Delayed neutron fraction (β) was calculated from the following relation [5]:

$$\boldsymbol{\beta = 1 - \frac{k_p}{k_{eff}}}$$

K_p is the multiplication factor considering prompt neutrons only.

K_{eff} is the multiplication factor with prompt and delayed neutrons (total neutrons). The results indicate that UO_2 fuel has a higher value of β, while (Th+U233) has a lower value.

Fuel and moderator temperature coefficient of reactivity ($\frac{\partial\rho}{\partial T}$) in pcm/K are calculated at BOC. They are calculated from the following relation: [15]

$$\boldsymbol{\frac{\partial\rho}{\partial T} = \frac{\Delta K}{K_1 K_2 \Delta T}}$$

K_1 , K_2 is the initial and final multiplication factor after change in temperature ΔT of the fuel. The results indicate that all fuel types are of negative temperature coefficient of reactivity. Table (2) reveals that moderator coefficient of reactivity is also negative.

$$void\ coefficient\ of\ reactivity = \frac{K_{v-}K_{eff}}{K_v K_{eff\ x100}}$$

K_v multiplication factor when all core are void.

K_{eff} multiplication factor for normal states. and difference is divided by the two values of K and 100 to get results by ΔV %. For example, to get 100 % void, the results are multiplied by 100 and for 1 % void the results are multiplied by 1

Table (2): Safety and kinetic parameters for fuel

	UO_2 Fuel	UN Fuel	UN+ZrO_2 Fuel	Th+U-235 Fuel	Th+U-233 Fuel
Λ Prompt life time (μs)	17.88	15.70	16.69	18.21	15.85
β (pcm)	771.74	691.29	666.17	659.1	377.04
α_f ($\frac{pcm}{K}$)	-1.168	-1.418	-1.376	-1.347	-1.054
α_m ($\frac{pcm}{K}$)	-14.07	-11.49	-23.48	-21.46	-13.5
void coefficient/ΔV %	-211.65	- 189.86	-209.04	-268.9	-170.56

Flux and Power Mapping distributions

Figure 13 (a, b,c,d,e) illustrates Radial Power distributions at BOC (beginning of cycle) across 1/6 of the assembly for Cases A,B,C,D and E respectively. The power distributions are normalized to the average value in the assembly. The power is higher near assembly periphery and the central water zone, also the power shows minimal values at the positions of burnable poisons rods both at the outer burnable poisons (at the assembly periphery) and inner burnable poisons (around central water zone). The power distributions are more flat in the assembly because the distributions of burnable poisons are both inner and outer. The maximum values at each case are 1.099, 1.111, 1.091, 1.122 , and 1.015 for cases A, B, C, D, and E respectively.

Figure (14) illustrates axial power normalized versus axial core height (cm) for all cases (A, B, C, D and E). The results have been calculated at BOC. The axial power is calculated at each case at position of the maximum radial power. The maximum axial power occurs at case E with fuel (Th + U-233). The axial distributions shows relatively higher values because the active length of the reactor is 120 cm. Typical values for cases A, B, C, D , and E are 1.504 , 1.803 , 1.5 , 1.77 , and 2.1 respectively

Figure (15) illustrates axial Thermal Flux (n/cm^2.s) versus axial core height (cm). The results have been calculated at BOC. The typical values for cases A, B, C, D , and E are 3.01x10^{13} , 2.28x10^{13} , 2.67x10^{13} , 3.18x10^{13} , 2.45x10^{13} (n/cm^2.s)

5- CONCLUSION

MCNPX code is used to model an assembly of KLT-40S Floating Reactor. Five different fuel types are tested for possible improvement of neutronic parameters. The tested fuels include UO_2 , two types of Uranium nitride (UN) and Two types of thorium fuel (Th). The results indicated that replacement of UO_2 by UN and (Th+U-233) increases the cycle length by 24 % and 17 % respectively. Gadolinium burnable absorber rods were burnt and became negligible after approximately 550 days. UN fuel has a higher fissile plutonium production rate while thorium mixed with U-233 has a lower minor actinides production rate (Pu+ Np-237). Burnable poison distributions (inner and outer) contribute to flat the radial power distributions.

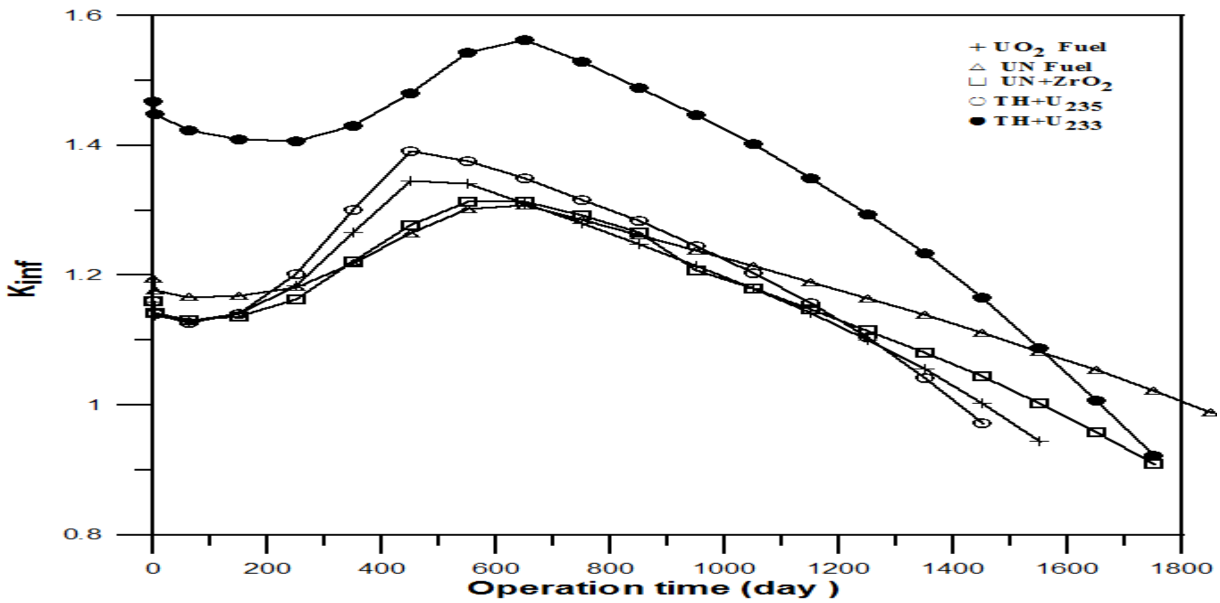

Fig. (3): K_{inf} against operation time (day) for different fuel types

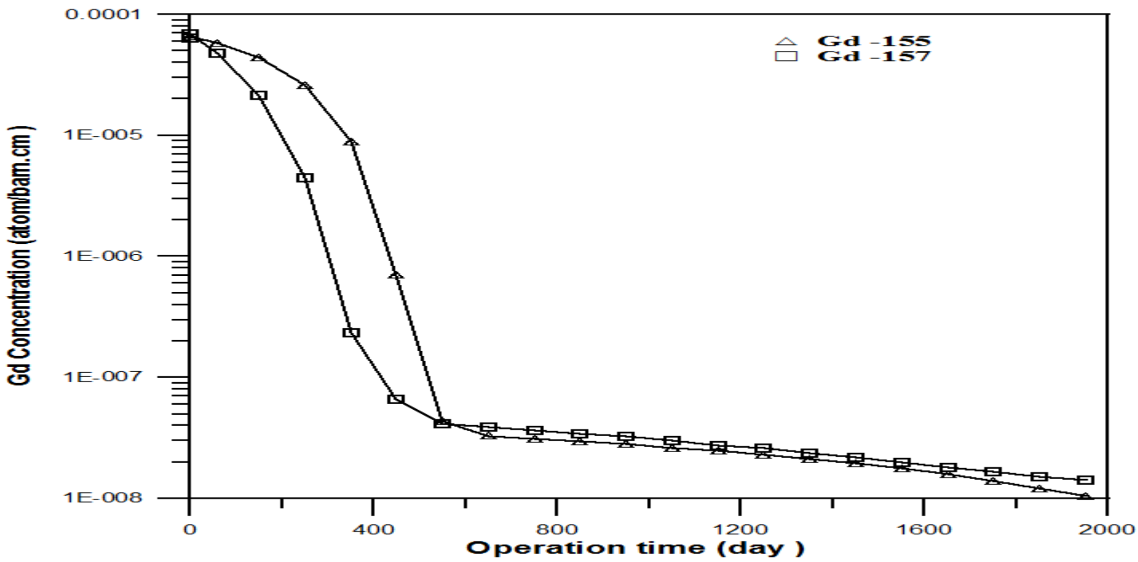

Fig. (4): Gadolinium isotopes concentrations against operation time for case A (UO_2 fuel)

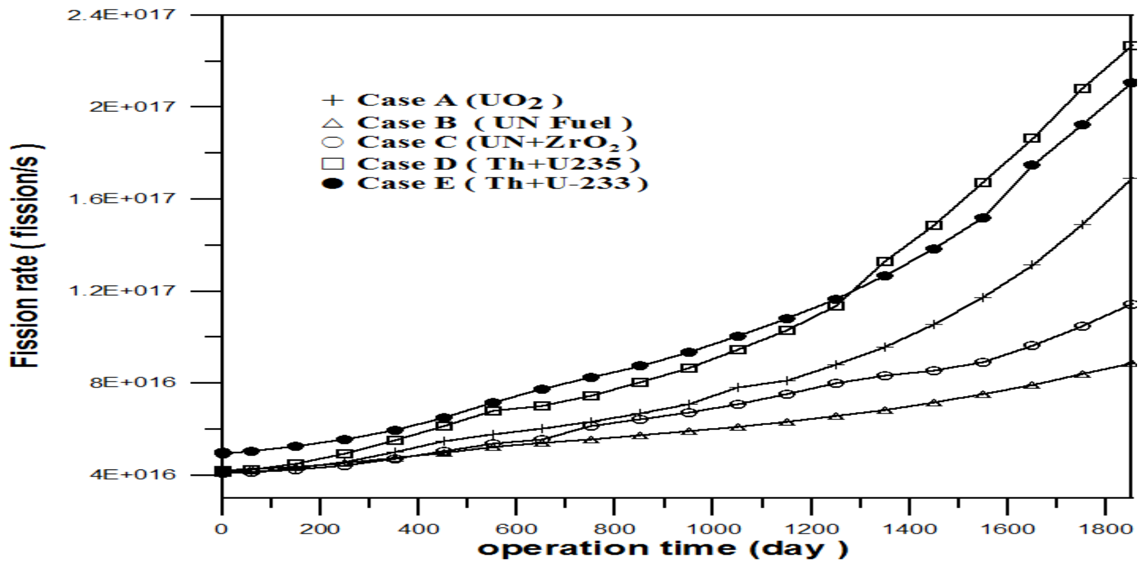

Fig. (5): Fission rate (fission/s) against operation time (day) for the assembly

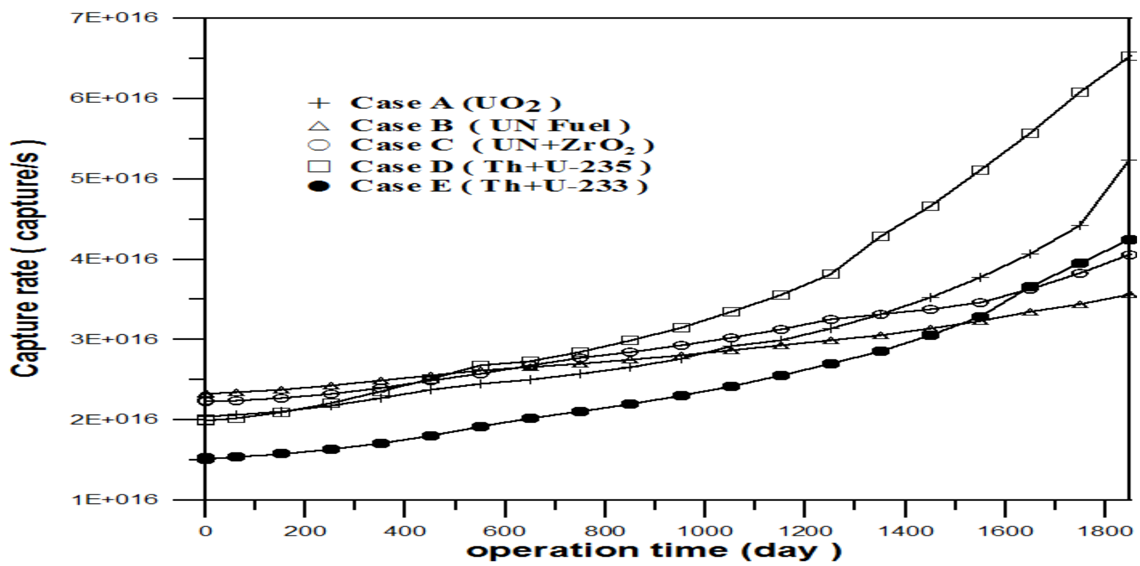

Fig. (6): Capture rate (absorption/s) against operation time (day) for the assembly

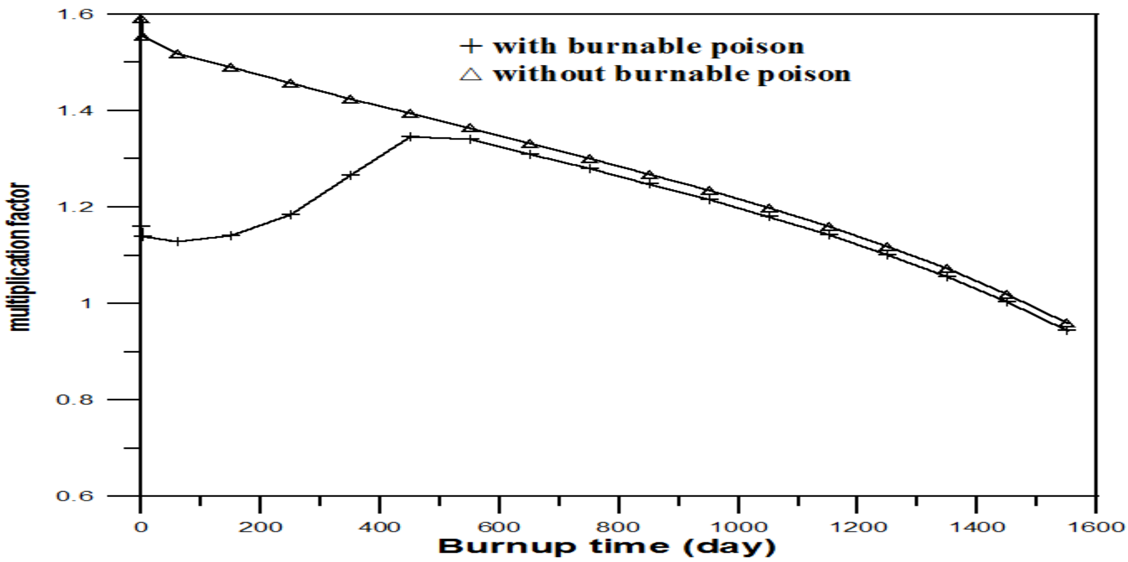

Fig. (7): K_{inf} for the assembly for UO_2 fuel with and without burnable poison versus burn up time (day)

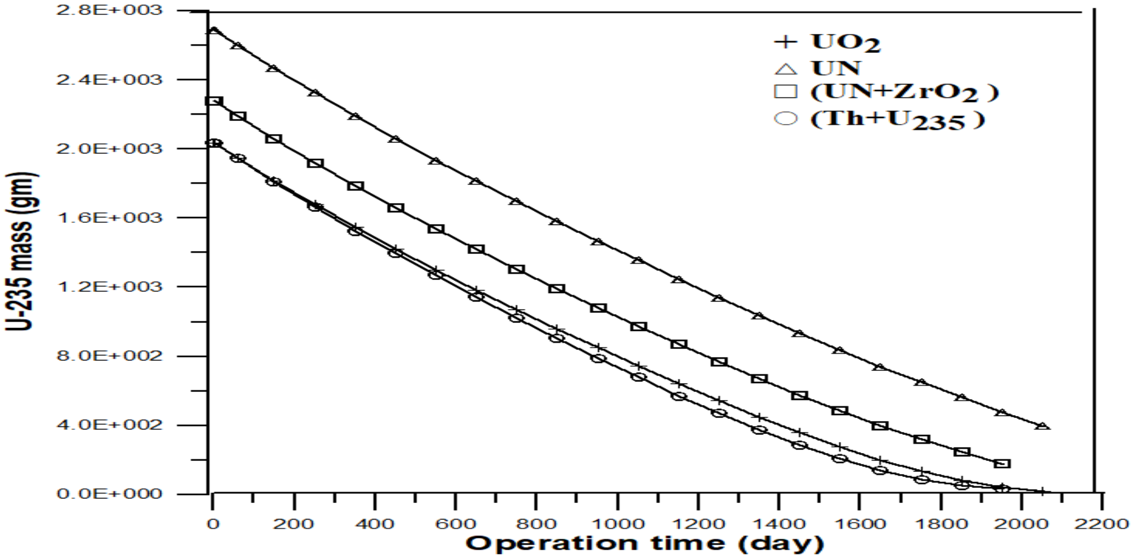

Fig. (8): Uranium 235 mass (gm) against operation time (day) for different fuel Types

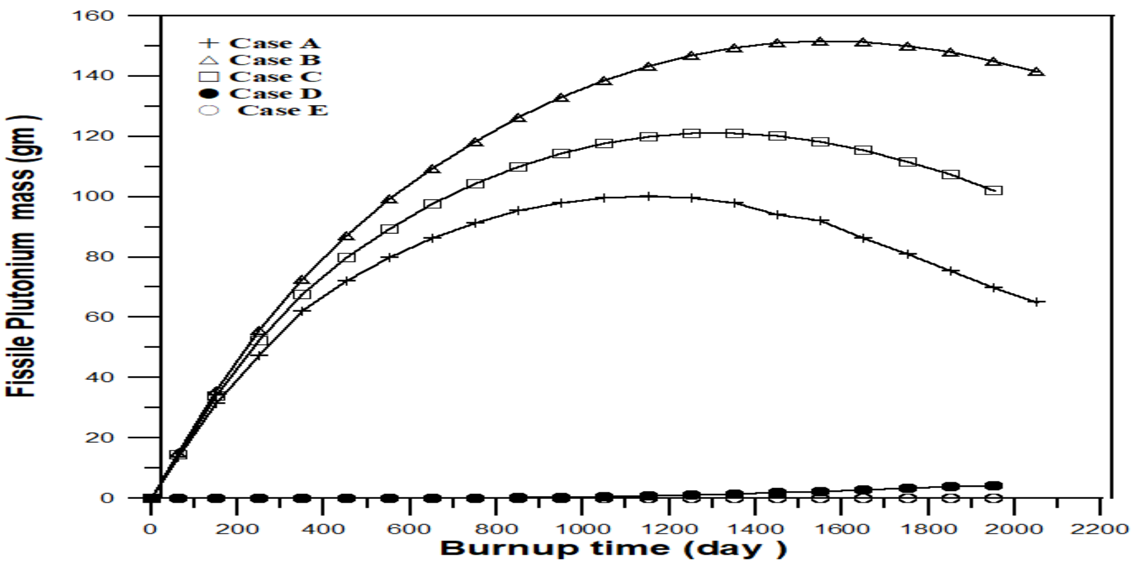

Fig. (9) : Total Pu - fissile against burnup time (day) for different fuel types

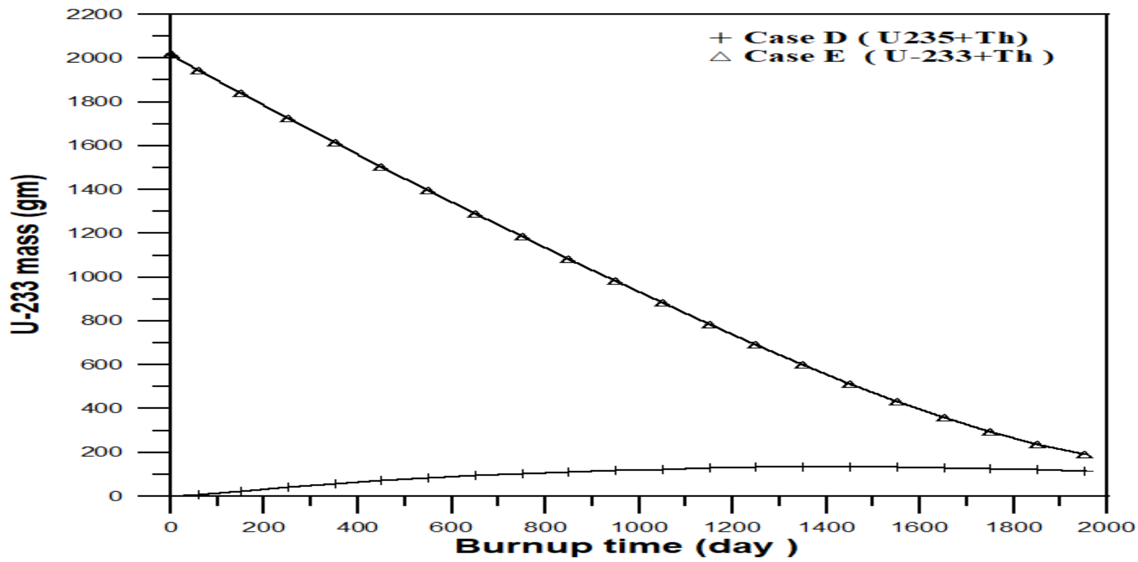

Fig. (10): U-233 mass (gm) against burnup time (day) for cases D and E

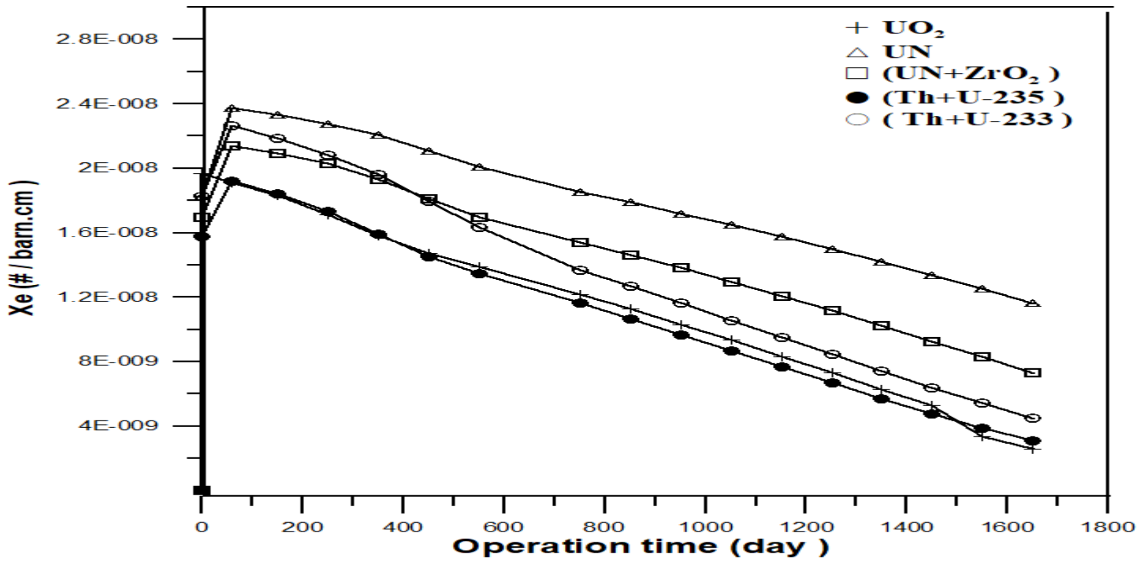

Fig. (11): Xenon-135 (atom/barn.cm) against operation time (day)

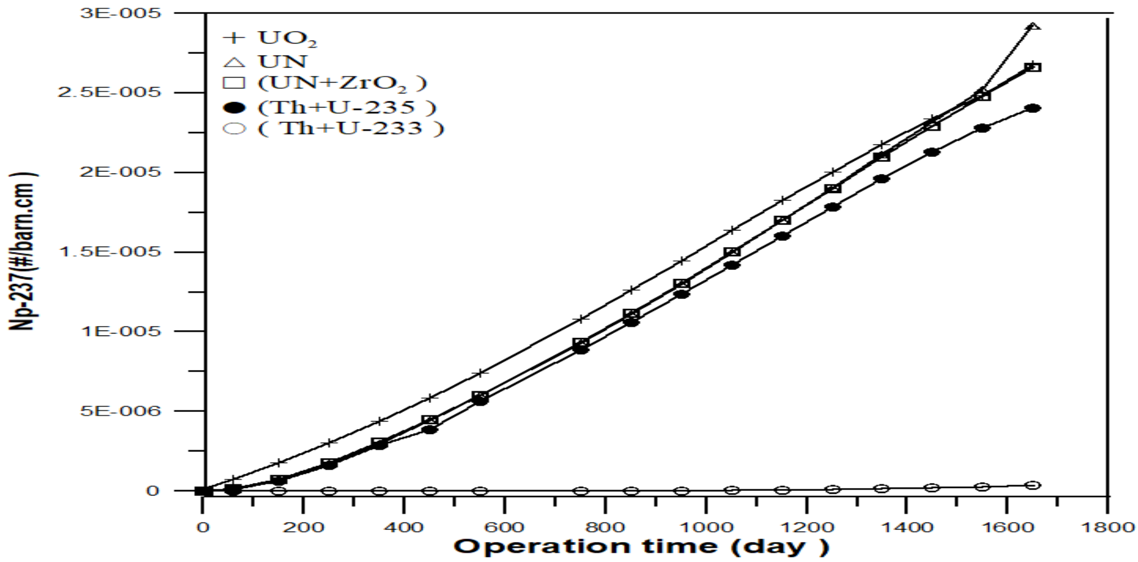

Fig. (12): Neptonium-237 (atom/barn.cm) against burnup time (day)

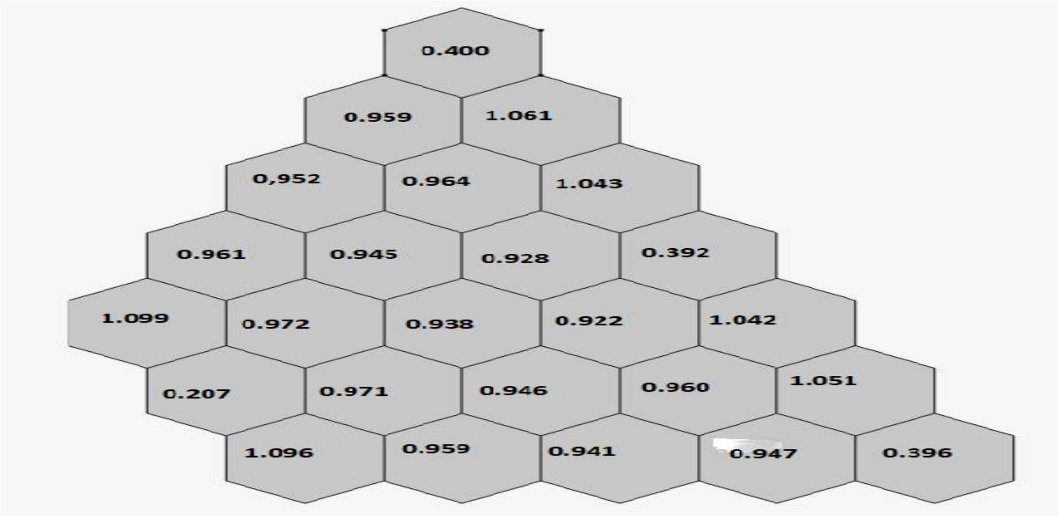

Fig. (13.a) :Radial Power distributions across 1/6 of the assembly for Case A

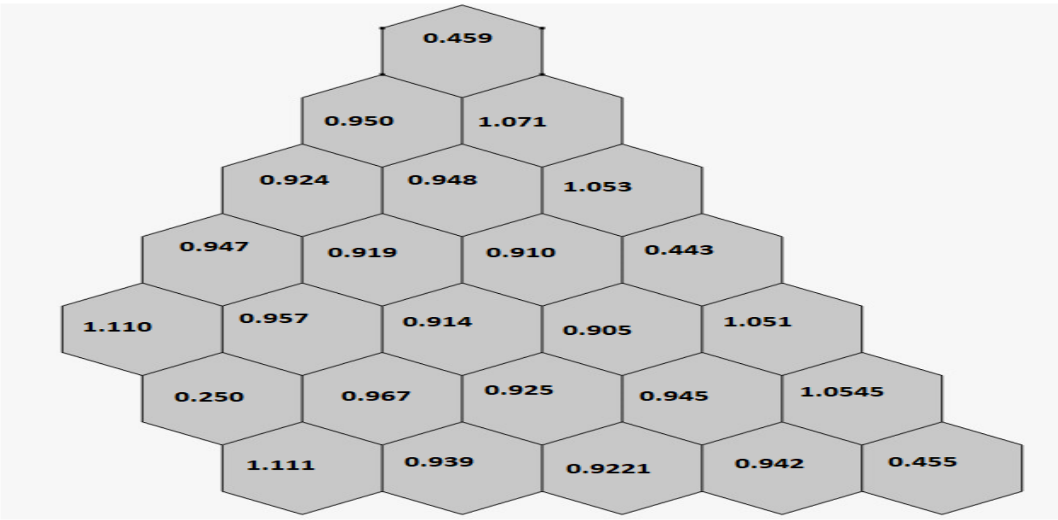

Fig. (13.b) : Radial Power distributions across 1/6 of the assembly for Case B

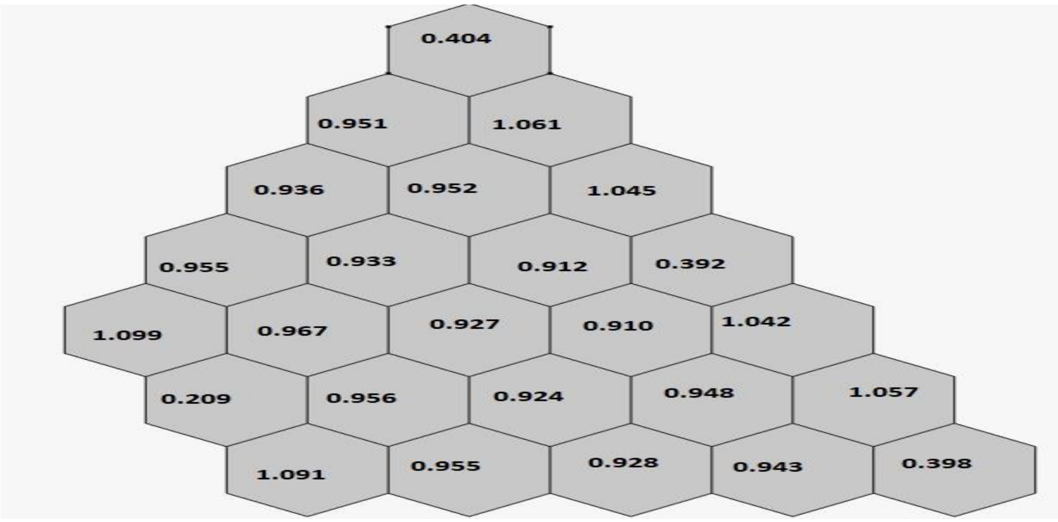

Fig. (13.c): Radial Power distributions across 1/6 of the assembly for Case C

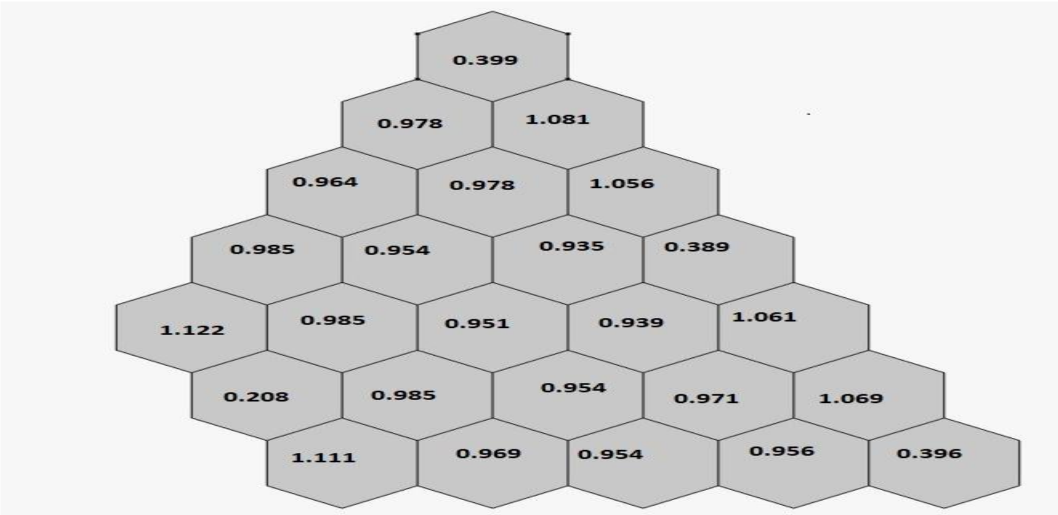

Fig. (13.d): Radial Power distributions across 1/6 of the assembly for Case D

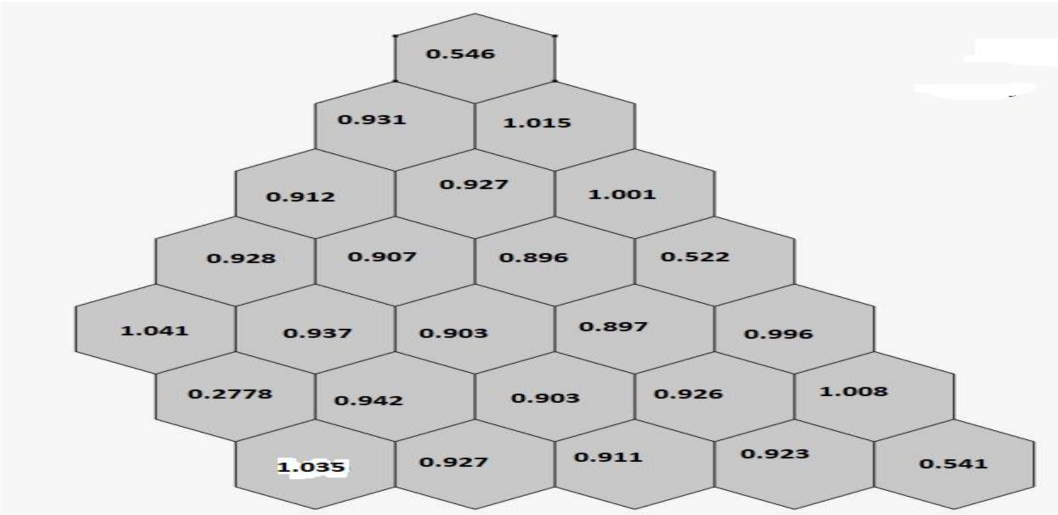

Fig. (13.e): Radial Power distributions across 1/6 of the assembly for Case E

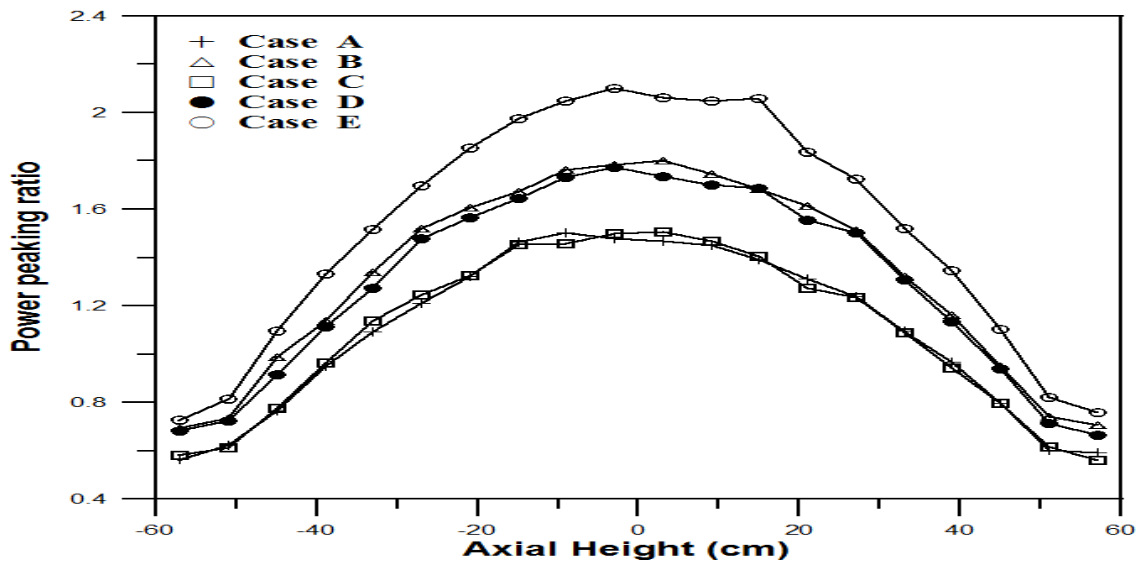

Fig. (14): Axial power normalized versus axial core height (cm)

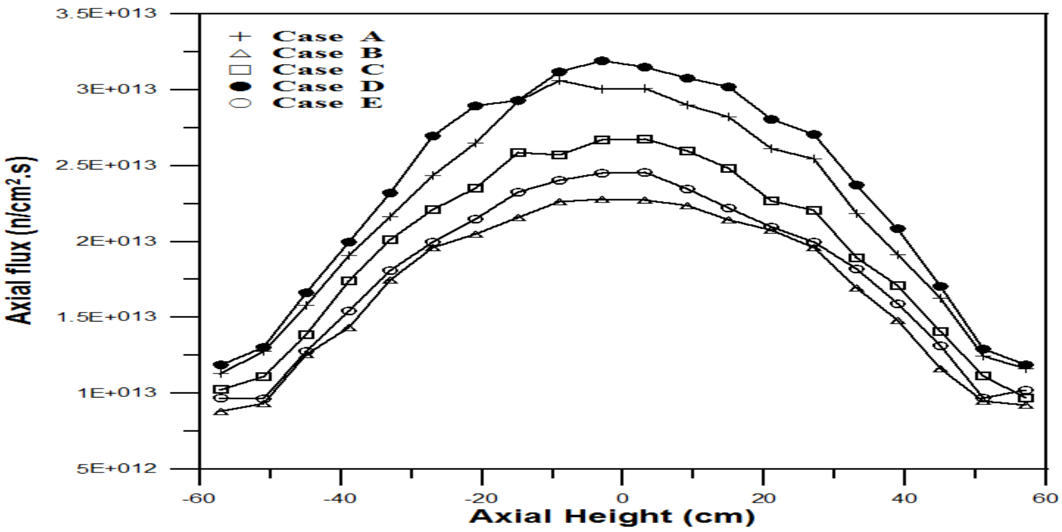

Fig. (15): Axial flux (n/cm^2. s) versus axial core height (cm)

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