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Core Optimization Simulation for a Pressurized Water Reactor

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Abstract: In this study, a research has been carried out for the design of an optimal core configuration for a TRISO fueled compact sized PWR core. This is a light water cooled and moderated reactor that employs TRISO fuel particles in zirconium-sheathed fuel rods. The combination of PWR technology and TRISO fuel has been preferred for research to get the benefits of TRISO fuel in terms of enhanced integrity against the release of fission fragments and high negative temperature coefficient of reactivity in well proven PWR technology. This PWR design possesses additional safety features associated with the default design of TRISO fuel particle, which makes its use suitable even in a densely populated area. The designed core can be utilized for heating and desalination purposes or at any remotely located research facility. The current research study has been focused on the core configuration, instead of selecting one of the standard fuel lattices which are mostly being used in nuclear power plants; an inventive fuel lattice has been suggested for the optimal design. The TRISO fuel particle size and fuel pitch have also been optimized to achieve a compact size core. Neutronic transport theory lattice code WIMS-D/4 was used for the calculation of group constants (D, Σa and $v\Sigma f$) and infinite multiplication factor (k_∞). This calculated data were used in diffusion theory code CITATION for the purpose of achieving effective multiplication factor (k_{eff}) and estimated life of the core. The detailed and thorough analyses revealed that core configuration plays a dominant role in determination of compactness and excess reactivity of the core. The amount of excess reactivity has been increased and core size has been condensed by designing an optimal core.

Key words: Optimal fuel pitch, fuel kernel, PWR, TRISO fuel, zirconium, WIMS-D/4, CITATION

INTRODUCTION

The goal of this chosen research field is to design a compact PWR with a novel concept of utilizing TRISO fuel in PWR technology; this combination increases the reliability and worth of PWR technology. This innovative concept of utilizing carbon coated particle was initially originated by Kim *et al.* (1997), in which graphite has been used as moderator in light water cooled PWR. In this conceptual design pyrocarbon coated fuel particles which are normally used in high temperature gas cooled reactor (HTGR) has been utilized. These TRISO fuel particles tightly packed in carbon matrix increases thermal conductivity of the core. The similar ideas have also been studied and published by Shimazu and Nagai (2005) and Kauchi and Shimazu (2003) in which carbon coated particles has been utilized in PWR technology with graphite and light water as moderator. The current proposed design study is different from the aforesaid studies in many aspects which mainly include core configuration, core size, power output, TRISO fuel particle size, procedure adopted for analysis and simulation codes used for the design, etc. The study has been emphasized on core configuration for designing an optimal compact sized core which also possesses enough excess reactivity required for at least 1 year full power operation. Instead of selecting standard core fuel lattice which are being used in most nuclear power plants, efforts have been made to design an inventive fuel lattice for the optimal design. For this purpose a few possible fuel lattice have been considered for core optimization. Furthermore TRISO particle size and fuel pitch have also been optimized for the optimal compact core design.

CORE DESIGN

A well known Tristructural-Isotropic (TRISO) micro fuel particle consists of fuel kernel composed of any suitable fuel like UO_2, UC, UCO or PuO_2 at the center and 4 consecutive layers of three isotropic materials, is shown in Fig. 1. Fuel kernel is surrounded by low density carbon buffer and three isotropic layers. These three layers

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consist of inner dense pyro-carbon (IPyC), SiC and outer dense pyro-carbon (OPyC). The low density carbon buffer accommodates fission gases released during reactor operation. The SiC layer provides the main structural strength to fuel particle and collectively these layers provide retention barrier against the release of fission fragments.

TRISO fuel particles are tightly packed in zircaloy sheathed fuel rod where empty spaces are filled with helium gas. This fuel rod arrangement is similar to ordinary PWR fuel rod except spherical fuel particles are being used instead of cylindrical fuel pellets. These fuel rods are arranged in different core configurations and all considered core have same number of fuel and control rods. There are total 416 fuel rods and 25 control rods in all cores. The height of fuel rod is 80 cm with the diameter of 3 cm. This is a small reactor which has only 25 MWth power output. The main design parameters are given in Table 1.

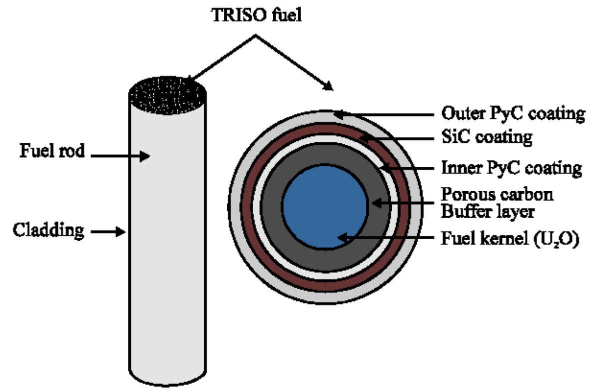

Fig. 1: TRISO fuel particle and fuel rod design

Table 1: Design parameters

Parameters	Dimension
Power out put	25MWth
Core height	~ 1 m
Core width	~ 1 m
Fuel rod height	80 cm
Fuel rod dia	3 cm
Cladding thickness	1.5 mm
Number of assemblies	1
Fuel type	TRISO
Fuel enrichment	9%
Cladding material	Zircaloy
Coolant	Light water
Moderator	Light water
Fuel pitch	4 cm
Primary coolant average temp	200°C
Primary system pressure	6 MPa
No. of shutdown rods	20
No. of regulating rods	5
Reflector	Beryllium
Reflector thickness	8 cm
Burnable poison	Gadolinia
Control rod material	Hafnium

Compact core modeling technique: The four layers of the TRISO particles have been homogenized to one zone according to their volume average nuclide densities. The heterogeneous effect has been neglected and it was supposed that the fuel rods were filled with homogeneous mixture of TRISO particle materials. The amount of these materials was calculated according to the dimension and densities of the particle layers. In addition to the enhanced integrity of design this situation would be very useful for the neutron moderation, most of the fission neutrons would be moderated by the graphite present in the fuel rod.

In this study WIMS-D/4 and CITATION computer codes are used to simulate the design of a compact nuclear reactor core.

WIMS-D/4: One-dimensional transport theory code WIMS-D/4 has been used for the generation of group constants, cross sections and infinite multiplication factor for fuel, moderator, reflector and control elements. This code provides the cell-averaged cross-sections and other lattice parameters for overall space dependent reactor calculations. It uses its own 69-group library of UK origin, which includes 14 fast, 13 resonance and 42 thermal neutron groups (Deen and Woodruff, 1995). Annulus geometry modeling option of WIMS-D/4 has been utilized for fuel rod, control rod and reflector. In this technique a fuel unit cell consists of fuel region at the centre and then is followed by a tiny gap and cladding Can and moderator region. The fuel pin modeling is shown in Fig. 2. The supper cell modeling technique is used for control rod and Power Card has been utilized for the burn up study of the designed core.

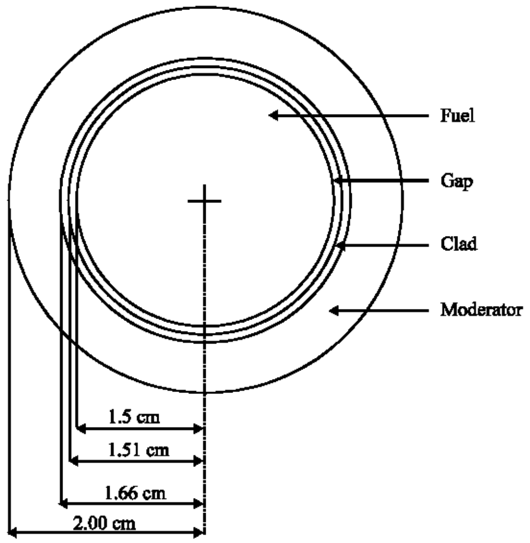

Fig. 2: Unit cell geometry of fuel pin

CITATION: The computer code CITATION solves the finite difference diffusion equation representations of neutron transport in zero (point), one, two and three dimensions. Wide range of geometries such as slab, cylindrical, spherical, hexagonal and triangular can be modeled by the code. The code determines the neutron multiplication factor, k_{eff}, by solving the neutron flux eigen-value problem by using finite-difference diffusion theory approximation of the neutron transport equation by direct iteration method. The code computes the effective multiplication factor, flux and power profiles in the core either by using microscopic or macroscopic cross-sections. In addition to this, the code can calculate reactivity feedback coefficients, effective delayed neutron fraction and prompt neutron generation (Fowler *et al.*, 1971).

Linking code: A comprehensive FORTRAN code was compiled which converts WIMS-d/4 out put data file into a specific format required by CITATION code.

Design assumptions: As the basic dimensions of the fuel rod, control rod and reflecting material are same in all the considered configurations, the group constants and infinite multiplication factor (k_∞) are same for all the cores. Only the value of effective multiplication factor (k_{eff}) or excess reactivity and compactness are the dominating factor for the selection of optimal core design.

For the purpose of the current study following design limits and assumptions have been followed:

- Fuel density has been set to 10.88 g cm^{-3}
- The heterogeneous effect related to TRISO fuel has been neglected
- To study the effect of fuel pitch on group constants and multiplication factor exclusively it was assumed that all the control rods were out of the core and in the absence of the control rod, region is supposed to be occupied by the moderator i.e. water
- A maximum 9% fuel enrichment has been chosen for the design study
- Each considered core is reflected by 8 cm thick beryllium layer from all the sides

RESULTS AND DISCUSSION

TRISO fuel particle size optimization: For the purpose of designing an under moderated core, group constants and infinite multiplication factor (k_∞) were calculated as a function of TRISO fuel diameter. In this analysis fuel kernel diameter was increased from 100 to 600 μm while keeping the thicknesses of outer four layers fixed. The dimensions and composition of TRISO fuel particle are given in Table 2 which can easily be made with current fabrication technology (The Citizen's Compendium, 2008). For each value of the kernel diameter, fuel pitch was varied over the suitable range and corresponding values of group constants and multiplication factor were obtained from the WIMS-D4 code. The value of k_∞ as a function of fuel pitch with TRISO fuel particle size as a parameter is plotted in Fig. 3. It is evident from the Fig. 3 that for small values of fuel kernel diameter, the value of k_∞ decreases as the fuel pitch is increased. But for the modest values of kernel diameter the value of k_∞ first increases as the fuel pitch is increased and then decreases after passing through a peak value. After the thorough analysis 400 μm fuel kernel diameter has been chosen for the design study, which in the optimal diameter because upon further increase in the diameter k_∞ does not increase significantly.

Table 2: TRISO fuel particle dimension and composition

Material	Density (g cm^{-3})	Outer diameter (mm)
UO_2 fuel kernel	10.88	0.40
Porous carbon buffer layer	1.10	0.60
PyC coating	1.90	0.70
SiC coating	3.20	0.77
PyC coating	1.90	0.87

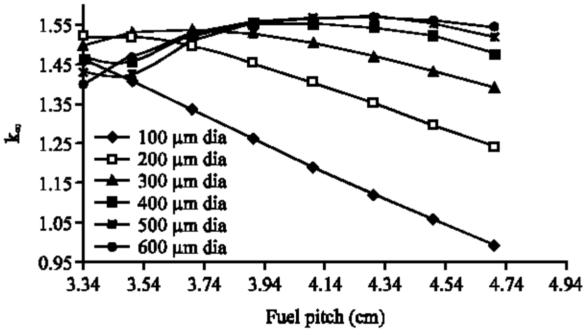

Fig. 3: k_∞ as a function of fuel pitch

Fuel pitch optimization: After the selection of TRISO fuel particle size, fuel pitch has been optimized from the corresponding fuel particle's curve shown in Fig. 4. The fuel pitch is selected from the curve where value of k_∞ is maximum under cold conditions. This is an optimum fuel pitch and in the case of a finite reactor operating at certain power level this value of fuel pitch will lie in an undermoderated region. It can be seen from the curve that k_∞ increases by increasing fuel pitch to a maximum value and drops thereafter, at this peak of the curve reactor is critically moderated. To the left of this peak, reactor is undermoderated and to the right of this point reactor is overmoderated. In the undermoderated region reactor has a negative temperature coefficient of reactivity mainly due to the Doppler effect and thermal expansion coefficient of water. The negative temperature coefficient of reactivity ensures the safety of the core, because an increase in moderator temperature will reduce its density, hence reduction in its moderation ability. This effect would harden neutron energy spectrum and therefore decreases the neutron multiplication factor. Whereas in an overmoderated system, the reactor is inherently unstable because multiplication increases as heat is added to the moderator. This in turn increases the heat generation in reactor core which is not the desired state of affairs (Aslam and Ahmad, 2002).

Optimal core configuration: After the selection of fuel particle size and optimization of fuel pitch, effective multiplication factor (k_{eff}) has been calculated by CITATION code for selection of optimal core design. The considered core sizes with effective multiplication factor and excess reactivity are shown in Table 3. It is evident from these analyses that core design No. 2 has the highest value of k_{eff} and core design No. 1 has the lowest value of k_{eff}. The core design which has highest value of k is not the most compact but it is lies at the middle and it is slightly larger than the most compact sized core design.

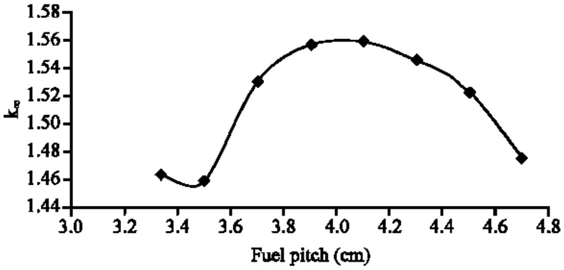

Fig. 4: k_∞ as a function of fuel pitch for 400 μm fuel kernel dia

Table 3: Core Sizes and their excess reactivity

Core design	Size (m)	k_{eff}	Excess reactivity (%)
No. 1	1.00×1.00×0.96	1.280	21.87
No. 2	1.08×1.08×0.96	1.310	23.66
No. 3	1.16×1.16×0.96	1.294	22.72
No. 4	1.16×1.16×0.96	1.290	22.48
No. 5	1.08×1.08×0.96	1.286	22.23
No. 6	1.08×1.08×0.96	1.295	22.78

The value of k_{eff} of the most compact core may be raised to 1.30 at the cost of 6% fuel enrichment increase. The difference in the sizes of design No. 1 and 2 is very minute therefore design No. 2 has been preferred with 9% fuel enrichment as it appears a better choice rather than utilizing design No. 1 with 15% fuel enrichment. All considered core configurations are shown in Fig. 5-10 and the selected core design is shown in Fig. 11. The small square in theses figures represents an equivalent cylindrical cell.

Core burnup analysis: The fuel inventory has been adjusted to obtain the desired amount of excess reactivity which should be sufficient for at least one year full power operation. For this purpose Power Card option available in WIMS-d/4 has been utilized for generation of cross sections and group constants and then CITATION code has been used to calculate the excess reactivity.

The required core inventory was calculated for one year full power operation at 25 MWth, which came out to be 200 kg of uranium (227 kg of UO_2). Burn up analysis of the designed core is shown in Fig. 12. The amount of excess reactivity present at the start of operation is 23.66% (~$ 36.40) which is sufficient for one year full power operation.

Safety analysis: The suggested design operates at much lower temperature and pressure than a standard PWR power reactor because of its specific use and the

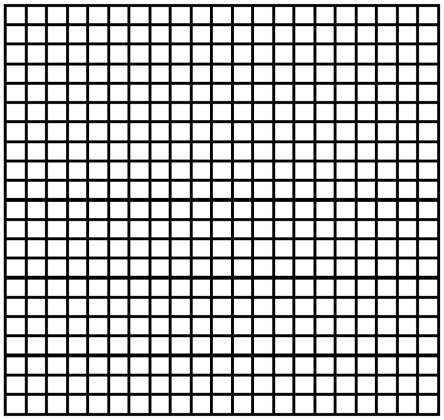

Fig. 5: Core configuration 1

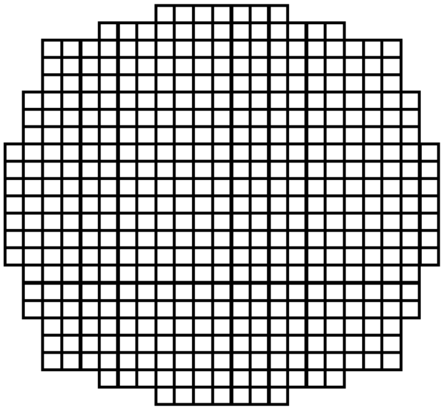

Fig. 6: Core configuration 2

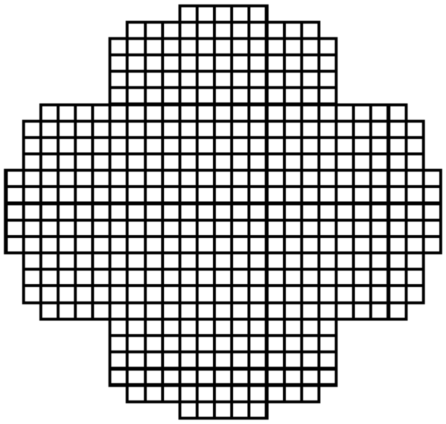

Fig. 7: Core configuration 3

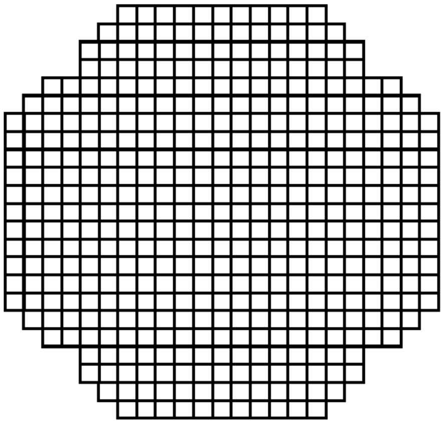

Fig. 9: Core configuration 5

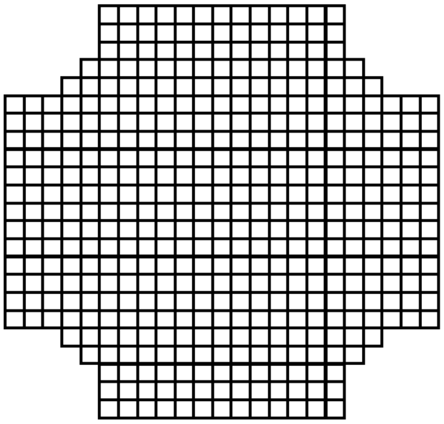

Fig. 8: Core configuration 4

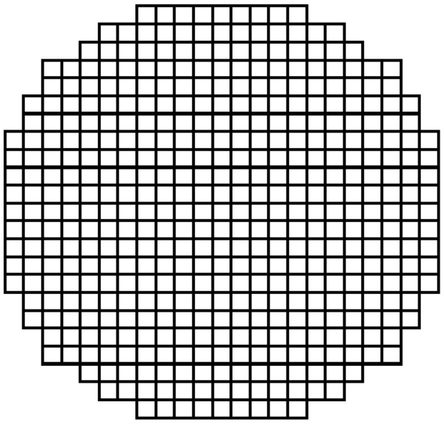

Fig. 10: Core configuration 6

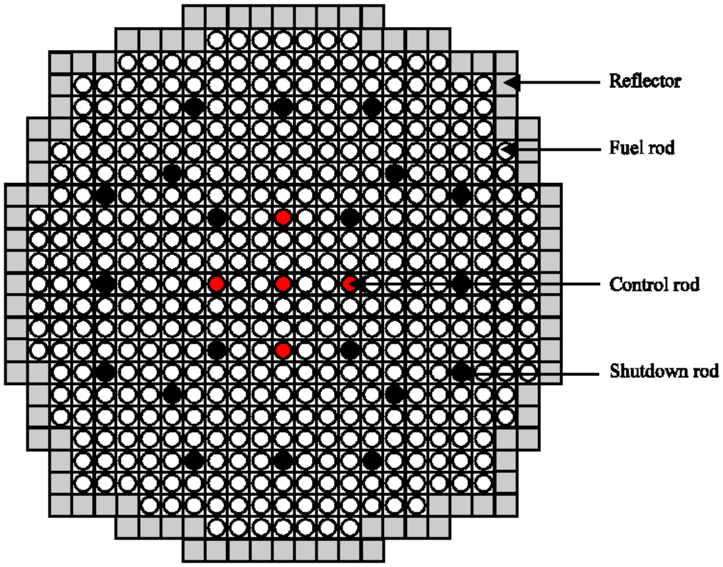

Fig. 11: Selected core configuration

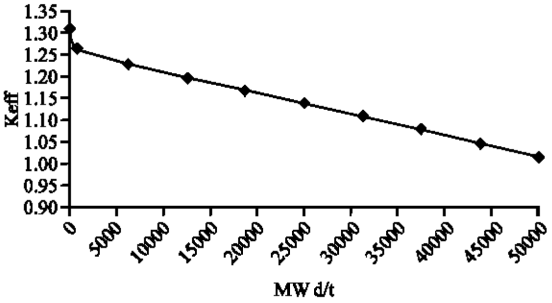

Fig. 12: Core burnup analysis

presence of TRISO fuel ensures retention of fission fragments at elevated temperatures. The reactivity coefficients were determined numerically from the gradients of reactivity curves and the average values of Doppler, moderator and void reactivity coefficients are -3.24, -32.47 pcm K^{-1} and -106 pcm/%void, respectively.

Control methodology: The control methodology for this design does not differ from that of a standard PWR, which consists of regulating rods, shutdown rods and burnup control mechanism. Hafnium has been chosen for the control and shutdown rods. Twenty shutdown and 5 regulating rods are used for the safe shut down and power regulating, respectively. These shutdown and regulating rods along burnable poison provide sufficient negative relativity for the safe shutdown. The total excess reactivity in the fresh fuel is 23.66% (~$ 36.40) which must be compensated by burnup control mechanism and control rods for operation. The total negative reactivity worth of these control and shutdown rods is 0.08632 (or -$ 13.28) when fully inserted in the reactor core. The remaining reactivity of $ 23.12 will be compensated by use of burnup control. The current study is focused only on the selection of optimal compact core configuration and therefore detailed study on chemical shim and burnable poison is beyond the present scope and is left for future study.

CONCLUSIONS

In this study, a study for an optimal core design of a compact PWR core has been carried out; this design utilizes TRISO fuel particles in zirconium-sheathed fuel rods. This particular fuel has been chosen for the current design study because of its superior reliability against the release of fission fragments and high negative temperature coefficient. Standard reactor neutronics simulation codes WIMS-D/4 and CITATION have been used for the design and neutronics analysis. A maximum 9% fuel enrichment has been set with beryllium used as reflecting material.

The current research study has been focused on the core configuration in which an inventive fuel lattice has been suggested for the optimal design. The TRISO particle size and fuel pitch have also been optimized to achieve the compact core. The selected TRISO fuel particle has 0.40 mm fuel kernel diameter in overall 0.870 mm outer diameter and the optimized value of the fuel pitch is 4 cm. The detailed analysis reveals that core design No. 2 among the considered cores is an optimal design because it has highest value of excess reactivity and it is also one of the smallest cores.

This study is focused only on the neutronics aspects of the design for selection of an optimal compact core. Further research study in this field would be detailed burn up analysis with suitable burnable poison, its thermal hydraulic analysis and radiation shield design.

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