Safety Features of a Pressurized Water Reactor Utilizing Coated Fuel Particles With a Novel Composition

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In this research paper, a safety analysis has been carried out for the conceptual design of a compact sized pressurized water reactor (PWR) core that utilizes a tristructural-isotropic (TRISO) fuel particle with an inventive composition. The use of TRISO fuel in PWR technology improves integrity of the design due to its fission fragments retention ability, as this fuel provides first retention barrier within the fuel itself against the release fission fragments. Hence, addition of one more reliable barrier in well established PWR technology makes this design concept safer and environment friendly. A small amount of Pu-240 has been added in the fuel for excess reactivity control. This addition of Pu-240 in TRISO fuel reduces the number of burnable poison and control rods required for reactivity control, and completely eliminates the requirement of soluble boron system. The suggested design operates at much lower temperature and pressure than a standard PWR power reactor, and the presence of TRISO fuel ensures the retention of fission fragments at elevated temperatures. All reactivity coefficients were found negative for the designed core, and the shutdown margin has also been increased with the suggested TRISO fuel composition. [DOI: 10.1115/1.4000338]

Keywords: compact PWR, TRISO fuel, Pu-240, BP rods, heating, desalination

1 Introduction

It is a well known fact that natural resources of crude oil and gas are limited, whereas increased utilization of coal results in environmental degradation. So reliance on fossil fuel only for power production is not a wise approach to meet the overgrowing demands for electricity. Nuclear power reactors have achieved a competitive position in the energy sector as an economical solution of present and future energy crises. The goal of our chosen research field is to design a compact PWR with a concept of utilizing TRISO fuel in PWR technology for further development in the nuclear field. This idea of compact reactor can be a potential source of energy for heating, desalination, and limited electric power generation for a remotely located research facility. This innovative concept of utilizing carbon coated particle was initially originated by Kim [1] in light water cooled PWR, with graphite as moderator. In this conceptual design, pyrocarbon coated fuel particles, which are normally used in high temperature gas cooled reactor (HTGR), had been used. These tightly packed TRISO fuel particles in graphite matrix increases thermal conductivity of the core. The similar ideas were also studied and reported by Shimazu and Nagai in 2005 [2] and by Kauchi and Shimazu in 2003 [3], in which carbon coated particles were utilized in PWR technology with graphite and light water as moderator. Our proposed design is different from the subject studies as we have utilized novel TRISO fuel particle composition, in which a small amount of Pu-240 with 2.0 w/o has been added to the TRISO fuel particle in the place of U-238, which acts as the reactivity suppressor. By using Pu-240, concentration of Gd-155 in gadolinia and number of gadolinia rods can be reduced. So the BP optimization process becomes easy, and power distribution is also smoother. Detailed parametric studies were already carried out for the selection of fuel kernel diameter, fuel enrichment, fuel pitch, reflector material, and its thickness for the design of a compact core [4].

Generally, boric acid (H_3BO_3) is used as a chemical shim to partially control light water reactors (LWRs) and it is always used in conjunction with control rods to compensate for xenon transients, fuel depletion, and fission products buildup during core life. The core reactivity can easily be increased or decreased by varying the concentration of boric acid in the coolant. The utilization of the inventive TRISO fuel particle can completely eliminate the use of soluble boron system, as this soluble boron free (SBF) concept is more viable in small and medium size reactors (SMRs) because it makes the plant simpler and reduces the maintenance efforts by excluding such a complex system from the plant. So the utilization of inventive TRISO fuel particle can completely eliminate the soluble boron system, and the moderator temperature coefficient of reactivity can be made negative throughout the fuel cycle. Without this novel TRISO composition concept, SBF designs need to utilize a large number of burnable poisons (BPs) and control rods for excess reactivity control for safe operation. And the utilization of large number of BP and control rods distorts the power distribution and makes the BP optimization process very cumbersome [5]. The function of BP is to suppress the excess reactivity throughout the core life and particularly at early fuel cycle stages. Traditionally, boron oxide (B_2O_3), boron carbide (B_4C), and gadolinia (Gd_2O_3) are being used as BP in LWRs [6].

TRISO fuel was chosen for PWR design because it would not only give the additional retention space for the fission products, but it would also provide another barrier against the release of fission products [1]. These fuel particles have the temperature coefficient always negative and are designed to withstand the differential thermal expansion, fission gas pressure, and such other high stresses even at temperature beyond 1600°C. Thus, these provide superior reliability against the release of fission fragments and can retain the fuel even in the worst accident conditions [4].

Originally, these particles were developed for HTGRs. Currently, this fuel is being used in many theoretical and experimental research studies. Pebble bed modular reactor (PBMR) and prismatic block reactor are the two famous types of reactors, which use TRISO fuel. Both of the designs are Generation 4 reactors. Fluidized bed reactors [7] and near boiling reactor concept [8] were also designed by utilizing the TRISO particle fuel.

2 Core Design

TRISO fuel is a type of microfuel particle that consists of a fuel kernel composed of any nuclear fuel at the center and coated with four layers of three isotropic materials. A low density porous buffer layer, being the first layer, provides the retention space for released fission fragments from the fuel during irradiation. The other three layers are made up of a highly dense pyrolytic carbon (PyC), and a ceramic layer of SiC provide the structural integrity and contain the fuel at elevated temperatures.

In the current design study, inventive TRISO fuel particles have been utilized in zircaloy sheathed fuel rod instead of standard PWR fuel pellets, and empty spaces are filled with helium gas. The design comprises of a total of 416 fuel rods and 25 control rods arranged in a parallelepiped core configuration shown in Fig. 1.

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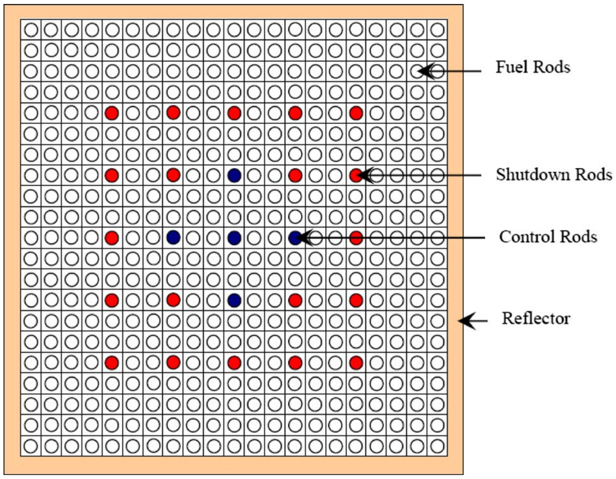

Fig. 1 Designed core configuration

This core configuration has been considered for the simplicity of the design and analysis. This is a small reactor, which only has 25 MWth power output; other main parameters of the design are given in Table 1.

In this study, WIMS-D/4 and CITATION computer codes have been used for the simulation of a compact nuclear reactor core. The Winfrith improved multigroup scheme version D/4 (WIMS-D/4) is a British origin code, which calculates cell averaged macroscopic cross sections and other lattice parameters for overall space dependent reactor calculations [9]. The code has been used for the generation of group constants needed as input for the 3D computer code, CITATION. The computer code CITATION solves the finite difference diffusion equation representations of neutron transport with a wide range of geometries [10]. The code determines the neutron multiplication factor (k_{eff}), flux, and power profiles. The code can also calculate reactivity feedback coefficients, effective delayed neutron fraction, and prompt neutron generation.

For the purpose of the current study, the following design limits and assumptions are followed [4].

(a) Fuel density has been set to 10.88 g cm^{-3}.
(b) The heterogeneous effect related to TRISO fuel has been neglected.
(c) The selected TRISO fuel particle has 0.40 mm fuel kernel outer diameter in overall 0.870 mm outer diameter.
(d) To study the effect of Pu-240 on excess reactivity exclusively, it was assumed that all control rods were out of the core during the analyses, and in the absence of control rod, the region is supposed to be occupied by the moderator.
(e) A maximum of 9% fuel enrichment has been set for design.
(f) Beryllium with 8 cm thickness has been used as reflector.

Table 1 Main parameters of the design

Power output	25 MWth
Core height	~1 m
Core width	~1 m
Fuel rod height	80 cm
Fuel rod diameter	3 cm
Cladding thickness	1.5 mm
Fuel type	TRISO
Fuel enrichment	9%
Coolant/moderator	Light water
Primary pressure	6 MPa
Primary average temperature	200°C
Cladding material	Zircaloy
Number of shutdown rods	20
Number of regulating rods	5
Reflector	Beryllium
Reflector thickness	8 cm
Control rod material	Hafnium (Hf)
Lattice type	Parallelepiped

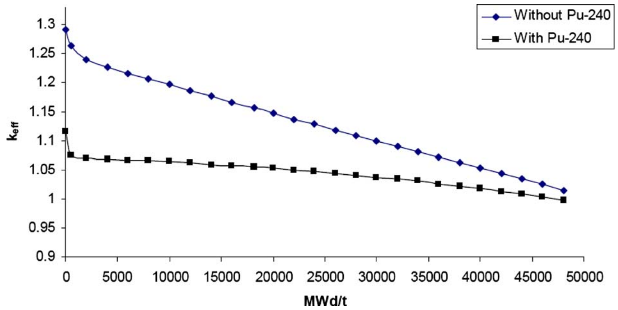

Fig. 2 Effect of Pu-240 on excess reactivity

3 Results and Discussions

3.1 Effect of Pu-240 on Reactivity. The novel TRISO fuel particle composition has 2 w/o of Pu-240 in the place of U-238 for reactivity control [11]. Pu-240 was selected from other nonfissile isotopes of plutonium as it has a higher thermal neutron capture cross section. The amount of excess reactivity of the core has been reduced significantly by using a small amount of Pu-240, and it also became flatter as compared with TRISO fuel composition without utilizing Pu-240. It is evident from Fig. 2 that the addition of Pu-240 reduces the excess reactivity throughout the fuel cycle; this reduction of excess reactivity is largest at the beginning of the cycle, then this difference gradually reduces, and at the end of the cycle, the effect of Pu-240 is almost finished. The rate of reduction of excess reactivity with an inventive TRISO fuel composition becomes slower over the entire cycle as compared with the original fuel, i.e., without Pu-240.

3.2 Safety Aspects of the Design. The designed core operates at much lower temperature and pressure than an ordinary PWR power reactor and the presence of TRISO fuel ensures retention of fission fragments at elevated temperatures. The reactivity coefficients were determined numerically from the gradients of reactivity curves shown in Fig. 3–5. The values of Doppler, moderator and void reactivity coefficients are −6.26 pcm/K, −29.50 pcm/K, and −176 pcm/%void, respectively.

The TRISO fuel particles possess some important safety aspects when directly cooled by water because it has a strong negative coolant and void reactivity coefficients. This allows the reactor to

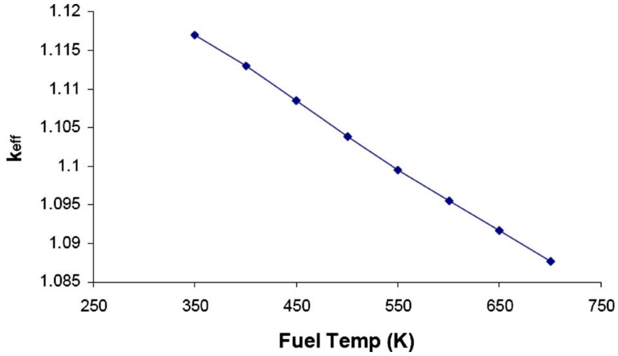

Fig. 3 Effect of fuel temp on k_{eff}

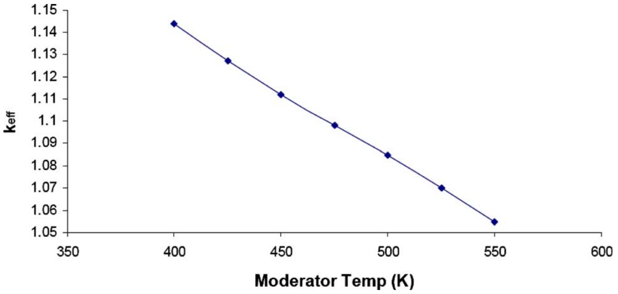

Fig. 4 Effect of moderator temp on k_{eff}

shutdown rapidly in undesired state of affairs, and during the emergency scenarios, only natural convection can cool down the core as the TRISO fuel accumulate very small amount of latent heat [12].

3.3 Increase in Shutdown Margin. Standard PWR control methodology has been used in the design study, which consists of regulating and shutdown rods and burnup control mechanism. Hafnium has been chosen for the control and shutdown rods material.

The total excess reactivity in the fresh fuel has been reduced to only 10.40% (\$ 16) from 22.56% (\$ 34.71) by utilizing 2 w/o of Pu-240 in TRISO fuel. Twenty shutdown and 5 regulating rods are used for the safe shut down and power regulating, respectively. 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 will be compensated by the use of BP. Study of BP is beyond the scope of the present study and is left for future work. However, it is anticipated that the excess reactivity can easily be decreased to a very small value around 0.14%, only by optimally utilizing BP, and therefore, the shutdown margin can be increased significantly.

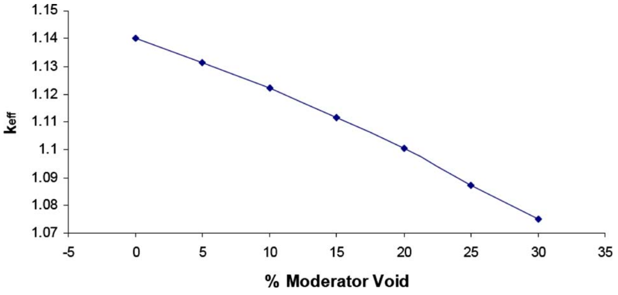

Fig. 5 Effect of moderator void on k_{eff}

4 Conclusions

Safety aspects of the designed core have been emphasized with a novel TRISO fuel composition for a conceptual design study of a compact PWR reactor core that employs TRISO fuel particles in zirconium-sheathed fuel rods in a light water cooled and moderated reactor. The operating temperature and pressure of the suggested design are much lower than any ordinary PWR power reactor because of its specific use, and the presence of TRISO fuel further ensures the safety because of its high thermal conductivity and small heat capacity. The reactivity coefficients of the designed core were determined, and all were found negative. The shutdown margin of the core has also been increased significantly.

Further work in this research field would be a detailed safety analysis by using the thermal hydraulic code RELAP-5, burnup analysis for the selection of BP, and radiation shield design.

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