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CRITICALITY CALCULATIONS OF THE FIXED BED NUCLEAR REACTOR

Farhang Sefidvash, Tomas Matela and Robson Silva da Silva
Nuclear Engineering Department, Federal University of Rio Grande do Sul,
Av. Osvaldo Aranha, 99 – 4° Andar
90046-900 Porto Alegre, RS, Brazil.
farhang@ufrgs.br

ABSTRACT

Small nuclear reactors without the need for on-site refuelling have greater simplicity, better compliance with passive safety systems, and are more adequate for countries with small electric grids and limited investment capabilities.

The Fixed Bed Nuclear Reactor (FBNR) is a small 40 MWe reactor based on the Pressurized Water Reactor (PWR) technology. FBNR is an integrated primary circuit and simple in design. It has the characteristics of being small, modular, proliferation resistant, inherently safe and passively cooled reactor with reduced adverse environmental impact. It utilizes the fuel designed for high temperature reactors operating in a relatively low temperature of PWR environment The 15 mm diameter spherical fuel elements are made of TRISO type microspheres embedded in graphite and cladded by SiC. The coolant flow transfers them from the fuel chamber into the core and become fixed forming a suspended core. Any accident signal will cut off the power to the coolant pump causing a stop in the flow. This results in making the fuel elements fall out of the reactor core by the force of gravity and return into the fuel chamber where they are passively cooled under subcritical condition. Therefore, the simplicity and passive safety characteristics of the reactor in the ambit of a well dominated technology, makes it a viable option for the near future deployment. Presently the reactor concept is being studied under the IAEA research contracts and is meant to be deployed through an international cooperation among various interested countries. For details visit www.rcgg.ufrgs.br/fbnr.htm .

In this paper the neutronics calculations of the FBNR are presented and the criticality of the reactor under different conditions are analyzed and evaluated.

1. INTRODUCTION

The Small Reactors without On-Site Refuelling are defined by IAEA "As reactors which have a capability to operate without refuelling and reshuffling of fuel for a reasonably long period consistent with the plant economics and energy security, with no fresh and spent fuel being stored at the site outside the reactor during its service life. They also should ensure difficult unauthorized access to fuel during the whole period of its presence at the site and during transportation, and design provisions to facilitate the implementation of safeguards. In this context, the term "refuelling" is defined as the ´removal and/or replacement of either fresh or spent, single or multiple, bare or inadequately confined nuclear fuel cluster(s) or fuel element(s) contained in the core of a nuclear reactor`. This definition does not include replacement of well-contained fuel cassette(s) in a manner that prohibits clandestine diversion of nuclear fuel material".

2. REACTOR DESCRIPTION

The Fixed Bed Nuclear Reactor (FBNR) is a small reactor (40 MWe) without the need of on-site refueling. It utilizes the PWR technology but uses the HTGR type fuel elements. It has the characteristics of being simple in design, modular, inherent safety, passive cooling, proliferation resistant, and reduced environmental impact.

The FBNR is modular in design, and each module is assumed to be fuelled in the factory. The fuelled modules in sealed form are then transported to and from the site. The FBNR has a long fuel cycle time and, therefore, there is no need for on-site refuelling. The reactor makes an extensive use of PWR technology.

It is an integrated primary system design. The basic modules, as shown in the schematic figure, have in its upper part the reactor core and a steam generator and in its lower part the fuel chamber. The core consists of two concentric perforated zircaloy tubes of 20 cm and 160 cm in diameters, inside which, during the reactor operation, the spherical fuel elements are held together by the coolant flow in a fixed bed configuration, forming a suspended core. The coolant flows vertically up into the inner perforated tube and then, passing horizontally through the fuel elements and the outer perforated tube, enters the outer shell where it flows up vertically to the steam generator. The reserve fuel chamber is a 40-cm diameter tube made of high neutron absorbing alloy, which is directly connected underneath the core tube. The fuel chamber consists of a helical 25 cm diameter tube flanged to the reserve fuel chamber that is sealed by the international authorities. A grid is provided at the lower part of the tube to hold the fuel elements within it. A steam generator of the shell-and-tube type is integrated in the upper part of the module. The control rods slide inside the core The reactor is provided with a pressurizer system to keep the coolant at a constant pressure. The pump circulates the coolant inside the reactor moving it up through the fuel chamber, the core, and the steam generator. Thereafter, the coolant flows back down to the pump through the concentric annular passage. At a certain pump velocity, the water coolant carries up the 15 mm diameter spherical fuel elements from the fuel chamber into the core. A fixed suspended core is formed in the reactor. In a shut down condition, the suspended core breaks down and the fuel elements leave the core and fall back into the fuel chamber. The fuel elements are made of TRISO type micro spheres used in HTGR.

The control system is based on the inherent safety philosophy that when all the signals from all the detectors are within the design ranges, the pump can operate, thus the normal situation of pump is "off" position.. Therefore, any initiating event will cut-off power to the pump, causing the fuel elements to leave the core and fall back into the fuel chamber, where they remain in a highly sub critical and passively cooled condition. The fuel chamber is cooled by natural convection transferring heat to the water in the tank housing the fuel chamber.

The pump circulates the water coolant in the loop and at the mass flow rate of about 141 kg/sec, corresponding to the terminal velocity of 1.64 m/sec in the reserve fuel chamber, carries the fuel elements into the core and forms a fixed bed. At the operating mass flow rate of 668 kg/sec, the fuel elements are firmly held together by a pressure of 10 bar forming a stable fixed bed. The coolant flows radially in the core and after absorbing heat from the fuel elements enters the integrated heat exchanger of tube and shell type. Thereafter, it circulates back into the pump and the fuel chamber. The long-term reactivity is supplied by fresh fuel addition and a fine control rod that moves in the center of the core controls the short-term reactivity. A piston type core limiter adjusts the core height and controls the amount of fuel elements that are permitted to enter the core from the reserve chamber. The control system is conceived to have the pump in the "not operating" condition and only operates when all the signals coming from the control detectors simultaneously indicate safe operation. Under any possible inadequate functioning of the reactor, the power does not reach the pump and the coolant flow stops causing the fuel elements to fall out of the core by the force of gravity and become stored in the passively cooled fuel chamber. The water flowing from an accumulator that is controlled by a multi redundancy valve system cools the fuel chamber as a measure of emergency core cooling system. The other components of the reactor are essentially the same as in a conventional pressurized water reactor.

2.1 Fuel Element Description

Coated particle fuel has been used for more than 30 years in nuclear reactors. These reactors have benefited from this fuel's higher burnup and temperature capabilities and its multiple barriers to fission product release. The use of a particle fuel form in LWRs has the potential to significantly increase burnup , safety margin, and proliferation resistance. In addition, it will reduce the fission product release relative to the present clad UO2 fuels. Using a coated particle fuel form tailored to a water-reactor environment can eliminate the constraints of the present pressurized water reactor (PWR) fuel system. Particle fuel reduces fuel temperatures, lowers stored energy, and has better fission product retention.

One of the significant features of the coated particle fuel form is the vast increase in surface area per fuel volume over the commonly used pellet and clad fuel.

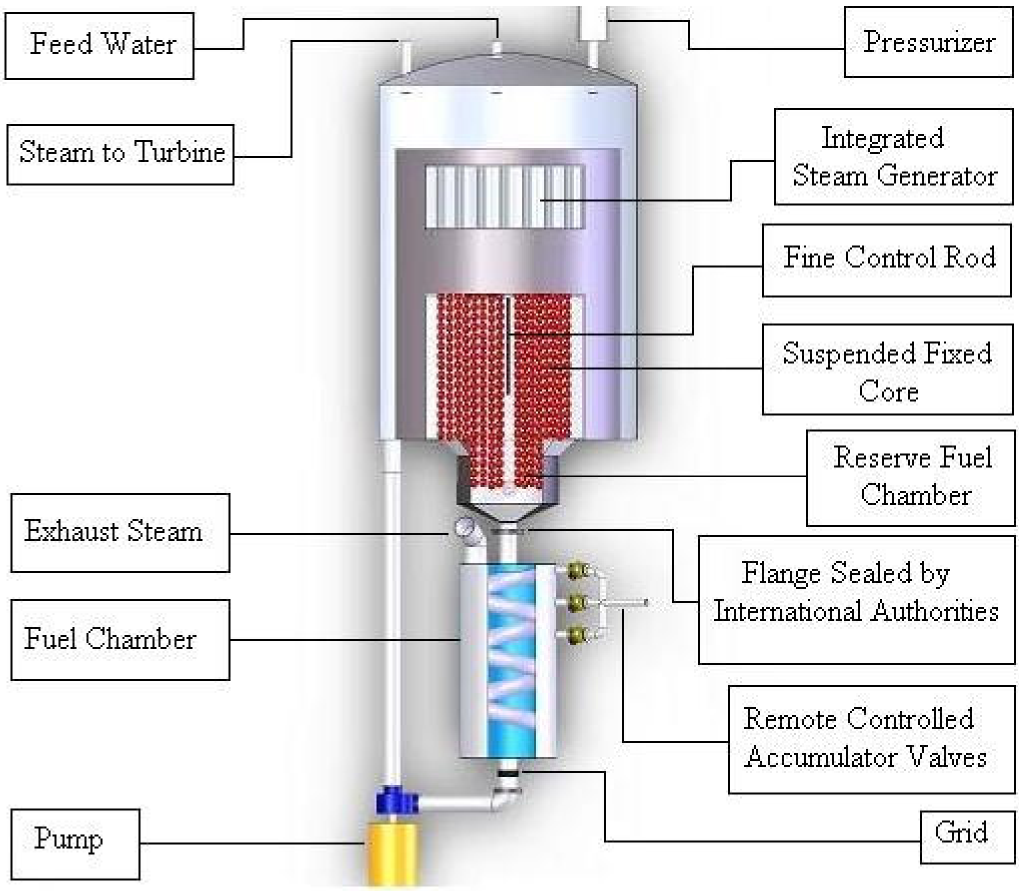

Figure 1. Schematic design of FBNR

Coated particle nuclear fuel has been irradiated to more than ten times higher than the present LWR range. This allows much greater energy extraction from the same amount of fuel, which results in less fuel throughput per energy produced. The reduction in spent fuel minimizes the burden on both temporary and permanent storage of spent fuel. This increase in burnup can also be used to provide longer fuel cycles, which is a significant benefit in refuelling reactors in remote locations or countries with modest infrastructure.

2.2 SCALE Computational Codes

SCALE (**S**tandardized **C**omputer **A**nalyses for **L**icensing **E**valuation) is a modular code system that was originally developed by Oak Ridge National Laboratory (ORNL) is utilized to make the neutronics calculations.

The 238-group ENDF/B-V library (238GROUPNDF5) is the most complete library in SCALE 5. This library contains data for all ENDF/B-V nuclides and has 148 fast and 90 thermal groups. The 238- and 44-group libraries are the preferred criticality safety analysis libraries in SCALE. The 44-group library is recommended for LWR systems, and the 238-group library is recommended for all other types of systems.

2.3 Reactivity as a Function of Enrichment

The reactivity as a function of enrichment for a single sphere was calculated. In case of the single cell, the values approach those of K_∞. The results are shown in Figure 2.

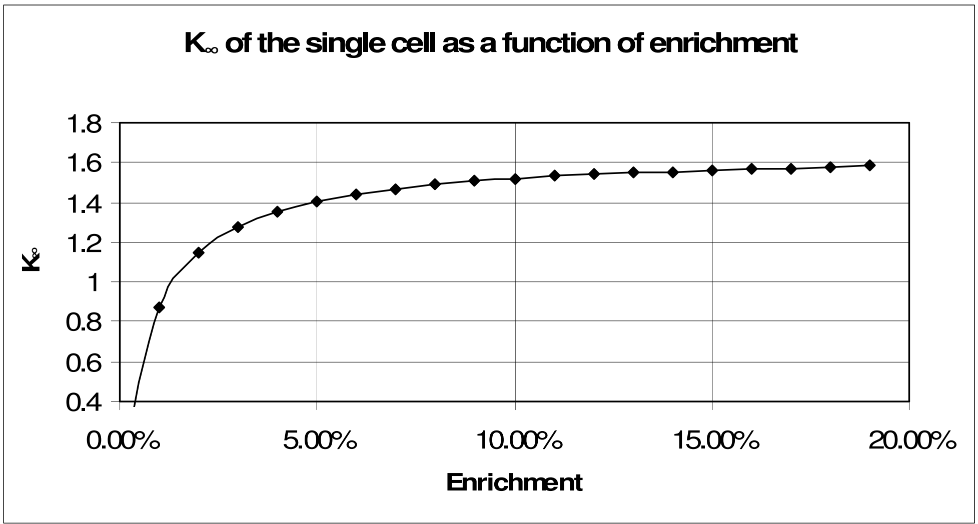

Figure 2. K_∞ for a single cell

Up to an enrichment of 5%, k_∞ increases considerably. After that point, k_∞ rises moderately up to the maximum of 1,79 for an enrichment of 99%. The reactivity for maximum hypothetical enrichment is investigated. k_∞ will be around 1.79 for a water moderated reactor and 1.82 for a graphite moderated reactor.

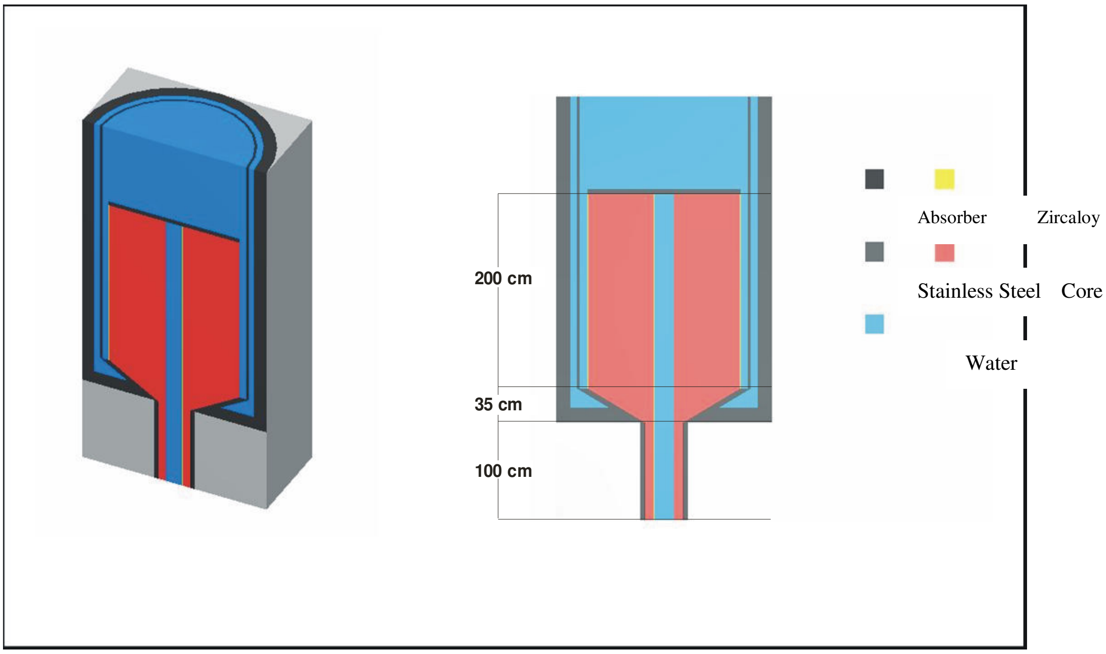

Figure 3. Keno VI model of homogenous reactor

2.4 Reactivity of the Reactor as a Function of Core Height and Enrichment

The global neutron multiplication factors of the reactor as a function of core height for enrichments of 2.2%, 5%, 9% and 19% are shown in Figure 4. Up to a value of about 120cm, the core height has a significant influence in reactivity. But as this influence is very low for core heights in the range between 120cm and 250cm, there is a need to use poison to reduce k_{eff} at the beginning of the burnup cycle. This possibility permits the use of higher enriched Uranium for an increase of core lifetime.

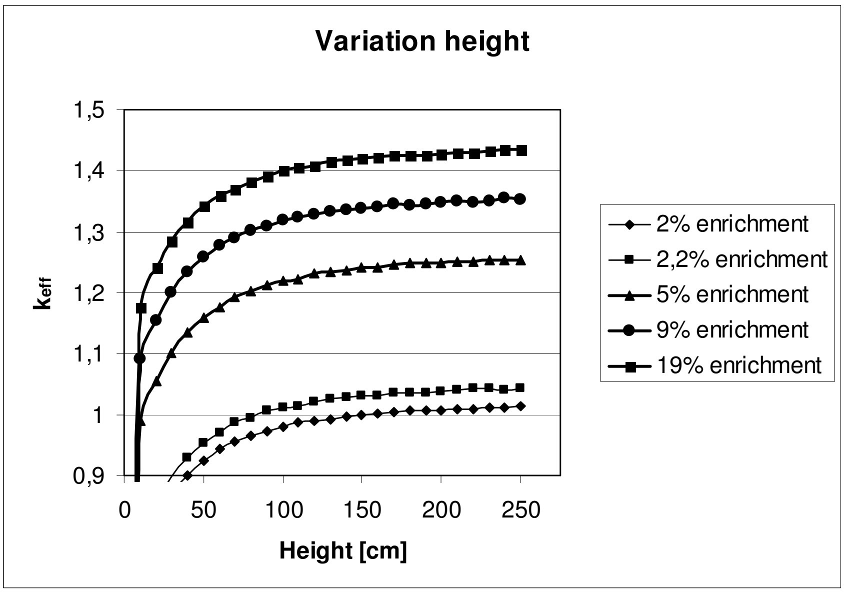

Figure 4. Variation of height for different enrichment values

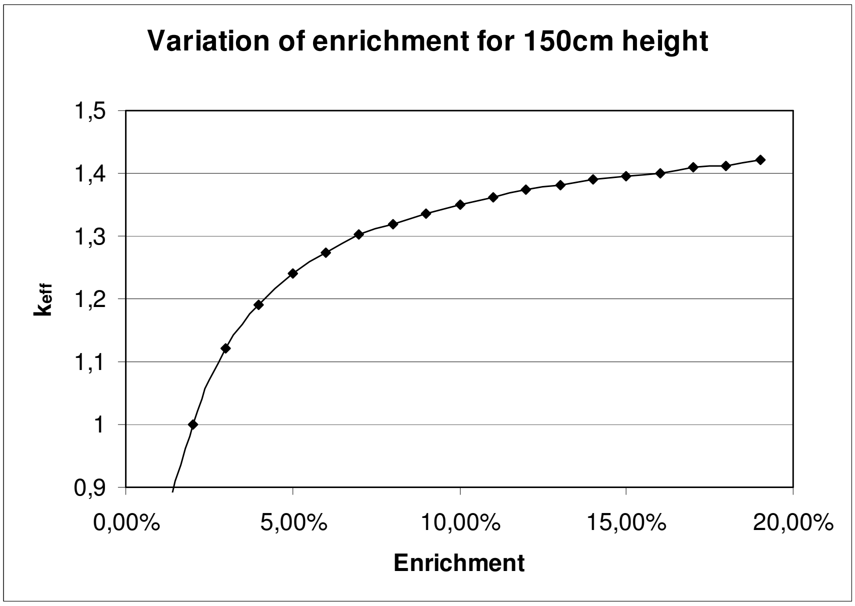

Figure 5. Variation of enrichment

The reactivity as a function of enrichment for a homogenous reactor was calculated for a height of 150cm (Figure 5). The maximal value was a k_{eff} of 1.421 for an enrichment of 19%.

3. CONCLUSIONS

The preliminary neutronics calculations show that the expected behavior of the FBNR is similar to a conventional PWR. The core lifetime can be as long as 17 years should the customer being ready to pay for the fuel of 19% enrichment. The 9% enrichment provides a lifetime of 7 years. In practice, this is not necessary as the reactor design involves the existence of small fuel chamber that can easily be changed. A 5% enriched reactor will require a change of fuel chamber only once every 3 years. The refueling involves the connecting and disconnecting of a 5 m^3 fuel chamber to the reactor by a flange that is sealed by the safeguard authorities.

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