The Basic Features of the FIXED BED NUCLEAR REACTOR FBNR

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Abstract. This paper presents the results of the assessment study of the basic features and characteristic of a small sized innovative nuclear reactor FBNR using the methodology developed under the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) of IAEA. The results indicate that FBNR innovative design comply with the basic principles and may be considered to be a fool proof nuclear reactor against nuclear proliferation. The greatest concern in relation to nuclear energy is non-proliferation and safeguard of the nuclear reactors.

The basic features of a new reactor type, the so-called Fixed Bed Nuclear Reactor (FBNR) is presented. FBNR is a small reactor (70 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 Nuclear Reactor is designed to bring about a new era of nuclear energy by promoting new philosophies and new criteria for the design of future nuclear reactors where the problems conceived about the present day nuclear reactors will be completely eliminated.

INTRODUCTION

The Small Reactors without On-Site Refueling are defined by IAEA "As reactors which have a capability to operate without refueling 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 [1, 2]. 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 "refueling" 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.

The first priority of the governments in relation to nuclear energy is non-proliferation and safeguard of the nuclear reactors. This is because the civilian nuclear technology can be misused or used as a cover for development of a nuclear weapons production capability. The challenges to the non-proliferation regime are evident worldwide. It is vital to the world security that all remain engaged in the development of proliferation-resistant nuclear reactors and technologies that can support any new arrangements to safeguard and internationalize the fuel-cycle and strengthen international institutions. The general recommendations given include (1) Increase the priority of proliferation resistance in design and development of all future nuclear energy systems, and (2) Develop & strengthen international collaborations on key proliferation-resistant technologies. The Fixed Bed Nuclear Reactor (FBNR) is designed to be a fool proof proliferation resistant nuclear reactor [3, 4]. The non-proliferation characteristic of the FBNR is based on both the extrinsic concept of sealing and the intrinsic concept of isotope denaturing.

Its small spherical fuel elements are confined in a fuel chamber that can be sealed by the authorities for continuous inspection. The only point of fuel diversion is at the fuel chamber flange that is monitored by a camera sending images to anywhere in the world through internet. Only the sealed fuel chamber needs to be transported from the fuel factory to the site and back. There is no possibility of neutron irradiation to any external fertile material.

Isotopic denaturing of the fuel cycle either in the U-233/Th or Pu-239/U cycle increases the proliferation resistance substantially. Therefore, both concepts of “sealing” and “isotope denaturing” contribute to the non-proliferation characteristics of the proposed reactor.

REACTOR DESCRIPTION

The Fixed Bed Nuclear Reactor (FBNR) is a small reactor (70 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 [5, 6].

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 refueling. The reactor makes an extensive use of PWR technology. It is an integrated primary system design. The basic modules have in its upper part the reactor core and a steam generator and in its lower part the fuel chamber, as shown in the schematic Figure 1.

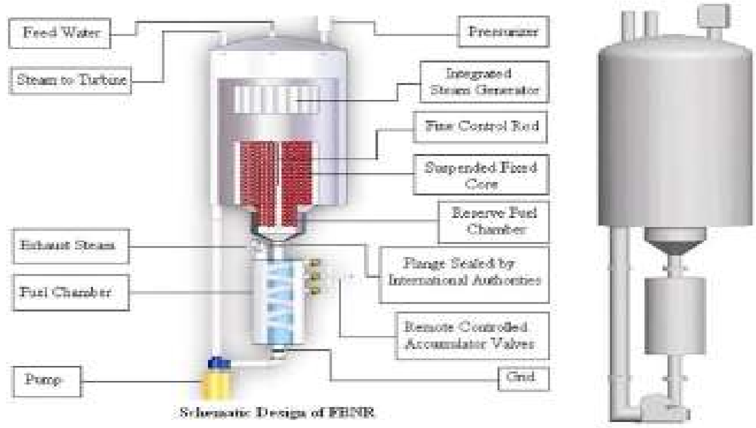

FIGURE 1. Schematic Design of FBNR

The core consists of two concentric perforated zircaloy tubes of 31 cm and 171 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 60 cm diameter tube made of high neutron absorbing alloy, which is directly connected underneath the core tube. The fuel chamber consists of a helical 40 cm diameter tube flanged to the reserve fuel chamber that is sealed by the national and 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. A control rod can slide inside the centre of the core for fine reactivity adjustments. 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 flow velocity called terminal velocity, the water coolant carries the 15 mm diameter spherical fuel elements from the fuel chamber up into the core. A fixed suspended core is formed in the reactor. In the shut down condition, the suspended core breaks down and the fuel elements leave the core and fall back into the fuel chamber by the force of gravity. The fuel elements are made of UO_2 micro spheres embedded in zirconium and cladded by zircaloy.

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, which is controlled by a multi redundancy valve system, cools the fuel chamber functioning as the emergency core cooling system. The other components of the reactor are essentially the same as in a conventional pressurized water reactor.

The fuel elements enter the reactor core and stay there suspended when the coolant flow velocity passes the velocity called "terminal velocity". The increase in the coolant flow velocity takes the elements out of the fuel chamber into the reserve fuel chamber and thereafter into the core in a vertical flow. The coolant's radial flow will occur only in the core as the core height limiter blocks the axial flow at the top of the core. Therefore, the fixed core is formed in a separate region below which is flowing pure coolant vertically at a velocity much higher than the terminal velocity. The so called "apparent weight" of the core is sustained by the vertical column of pure coolant flow. The radial flow serves to cool the fuel elements. The axial pressure drop of the coolant serves to compact the fuel elements in the core and makes it a fixed bed.

FUEL ELEMENTS

The spherical fuel elements are fixed in the suspended core by the flow of water coolant [7]. Any malfunction in the reactor system 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 become stored in the passively cooled fuel chamber under sub critical condition.

The fuel consists of coated UO2 kernels embedded in a zirconium matrix which is then coated with a protective outer zirconium layer. CERMET Fuels have significant potential to enhance fuel performance because of low internal fuel temperatures and low stored energy.

The FBNR fuel element consists of 500 microns in diameter UO_2 micro spheres covered by 25 microns thick zirconium cladding embedded in a spherical zirconium matrix that is cladded by 300 microns thick Zircaloy-4 cladding to form a 15 mm diameter fuel element, as shown in Figure2.

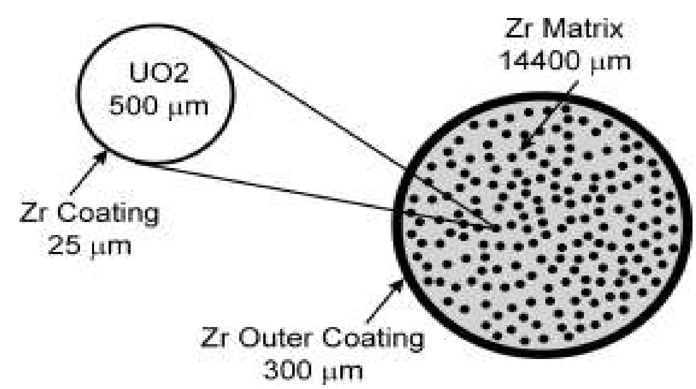

FIGURE 2. FBNR Fuel Element

THE CHARACTERISTICS OF FBNR

Small nuclear reactors best satisfy the needs of the future world specially that of developing countries. At a particular point in time, when a necessity to limit the emissions of carbon dioxide is acknowledged by the majority of countries, the small reactors will have a good chance to be implemented in many developing and industrialized countries and may contribute a lot to the sustainable development through both, electricity production and process heat applications[8,9,10].. Some of the important advantages of the FBNR reactors may be summarized as follows:

- FBNR is a small, simple in design, inherently safe and passively cooled nuclear reactor with reduced adverse environmental impact.
- FBNR uses a proven technology namely that of the conventional pressurized water reactors (PWR).
- The spherical fuel elements of HTGR type are fixed in the suspended core by the flow of water coolant. Any malfunction in the reactor system 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 become stored in the passively cooled fuel chamber under sub critical condition.
- FBNR is small in nature. The optimum size is about 70 MWe. The higher power can be achieved at the cost of a lower thermodynamic efficiency.
- The obvious simplicity of the design and the lack of necessity for complicated control system, make the reactor highly economic.
- The steam generator is housed within the pressure vessel having an integrated system, thus avoiding the problems associated with a possible steam generator leakage.
- Easy dismantling and transportability.

- The reactor can be operated with a reduced number of operators or even be remotely operated without any operator on site.
- They are adequate for countries with small electric grids and insufficient infrastructure.
- They are adequate for countries that have limited capacities for investment, especially in relation to hard currency, and small turnover of capital in the electricity market.
- They offer an option of electricity generation coupled with seawater desalination, which meets the urgent needs of many developing countries.
- They could offer a variety of passive safety features that may be difficult to obtain with large reactors. This fact makes them a good potential choice for countries with insufficient nuclear infrastructure and limited number of human resource.
- They are of particular interest for advanced future non-electric applications, such as hydrogen production, coal liquefaction, etc.
- They provide means for learning knowledge and technology from a small prototype plant.
- As nuclear reactors do not emit carbon dioxide, they will provide the developing and industrialized countries with sustainable development through both, electricity production and process heat applications.
- The spent fuel from FBNR may not be considered as waste, in a peaceful world of the future, as it can perform useful functions. Should reprocessing not be allowed, the spent fuel elements can easily be vitrified in the fuel chamber and the whole chamber be deposited directly in a waste repository. These factors result in reduced adverse environmental impact.

- The FBNR is a land-based nuclear power plant for urban or remote localities. The FBNR is designed to produce electricity alone or to operate as a cogeneration plant producing simultaneously: electricity, desalinated water, steam for industrial purposes and heat for district heating.
- No refueling on the site is necessary because the fuel elements are always in the sealed fuel chamber and transported to and from the factory for refueling under surveyed condition. Refueling is done by the replacement of fuel chamber. The length of the fuel cycle chosen depends on the economic analysis of the fuel inventory for particular situation of the reactor and its application.
- The size of reserve fuel chamber can be adapted to the need. The replacement of fuel chamber is done at any desired time interval and could be set at every 10 years or for the reactor lifetime.
- No reshuffling of fuel is necessary because the fuel elements go from fuel chamber to the core and back without the need of opening the reactor.
- There is no need for fresh fuel to be stored at the reactor site since the sealed fuel chamber is transported to and from the factory where the refueling process is performed. The spent fuel are confined in the sealed fuel chamber and kept cool by its water tank. It can be sent back to the factory at any time when the radiological requirements are met.
- It resist against “Terrorist Action”, “Explosion”, “Earthquake”, “Flooding”, “Fire”, “Tornado”, and “Bombing”. Any abnormal signal outside the range of operation from any of the detectors will signal an accident. In such a case the power is automatically cut off the pump and the fuel elements will fall out

of the reactor core by the force of gravity and become stored safely in the passively cooled fuel chamber.

- FBNR can be built in urban area as it is inherently safe and has a reduced environmental impact. Its underground containment building hides its industrial image and makes the nuclear power plant with FBNR an agreeable place to visit and can become a pleasant park or a garden for the city.
- The size of the nuclear reactor market On the basis of present is 2 TWe electricity generation worldwide where 350 GWe of which is nuclear, and considering a modest increase of 4% per year with the cheap plants costing about $1000 per KWe, the potential electrical energy market is about $800 billions per year. Any fraction of this market conquered by the FBNR is more than enough.
- The development of FBNR is not too expensive for a developing country to afford. The main investment comes from the international investors who recognize the profitability of investing in the innovative nuclear reactors. The host country principally will provide the financial, administrative and legal means for its deployment.

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